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(54) Title: ULTRASONIC TRANSDUCER SYSTEM WITH TEMPORAL CROSSTALK ISOLATION

(57) Abstract

Transducers are mounted in a housing or vessel to propagate signals along a fluid measurement path, and received signals are temporally or acoustically separated to remove crosstalk in the acoustic propagation paths of interest, which may be paths through the solid body of the housing or vessel or may be separate paths. These may be segments in a closed path circulation or swirl measurement, or different paths carrying combinations of possibly unrelated measurement signals. In one preferred embodiment, a single channel instrument processes signals from plural transducers which are connected in parallel to its processing input, greatly enhancing the effective system bandwidth and reducing equipment costs. Clamp-on circulation measurement or detection systems are described that allow easy evaluation and set-up of flow conditioning loops. A simple flange and O-ring structure provides a high degree of acoustic isolation, allowing two transducers to be placed within a single opening and beamed along directions to effect chordal closed loop interrogations. Reflectors may split the signal from one transducer to effect closed loop interrogations in adjacent or orthogonal planes. Flanged transducer casings allow transducers to be closely spaced in solid conduits or on rigid frames without ringing. Alternatively, isolation structures may be formed in a separate framework or holder, providing precise positioning for interrogating gases in unconfined or loosely confined regions. Closed path sensing configurations measure circulation, swirl, or mass flow.

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ULTRASONIC TRANSDUCER SYSTEM WITH TEMPORAL CROSSTALK ISOLATION

Related Applications

This application is related to the subject matter of PCT International Application PCT/US91/04563 published as WO92/00507 on 9 January 1992.

Background of the Invention

The present invention relates to ultrasonic transducer and measurement systems of the type wherein an electrically actuated signal source, typically a piezoelectric crystal, is mounted in a mounting assembly which may be fixed to a housing or wedge, or to a conduit, to propagate ultrasonic signals through a medium in the conduit. It particularly relates to such transducer and measurement systems wherein the medium has a low density, such as a gaseous medium and the signal of interest has a low energy level, or to systems wherein size of the conduit or signal path length through the medium raise considerations of crosstalk.

In these circumstances, the amount of signal energy which can be received through the medium is relatively small or difficult to distinguish. For example, the signal propagates through the gas with a velocity different from and generally much slower than its propagation velocity through the solid structure of the conduit, so it can be difficult to find a suitable timing window in which the received signal can be dependably distinguished from ringing or other energy which is propagated directly through the conduit walls with a generally high amplitude.

To some extent the problem of signal strength can be addressed by appropriate impedance matching and the use of a large-area diaphragm to couple the crystal to thc medium. However, suitable isolation remains a problem, particularly in view of the relatively large amount of energy contained in the solid-path noise band.

One approach to this problem has been discussed in the inventor's aforesaid International patent application. In that application, specifically with reference to Figure 15A thereof, a construction is shown involving acoustically massive rings or a spiral body interposed in the solid body acoustic path between the transmitting and receiving crystals. A number of related constructions are also shown, in which abrupt impedance changes occur along a path that includes thin-walled conduit, housing, mounting, or stand-off elements. The full disclosure of that patent application is hereby incorporated by reference herein. The present disclosure is directed to related constructions, further isolation structures, and

measurement systems with different practical embodiments of transducer isolation and mounting.

Brief Description of the Invention

In accordance with one embodiment of the present invention, a transducer is mounted to a housing, frame or vessel to propagate signals along a fluid interrogation path, and the noise propagation path through the solid body of the housing or vessel is arranged to delay or attenuate transmission of the solid signal, such that in multiple sampling windows, the fluid-transmitted signal is dependably received.

In one embodiment, a base, frame or lattice-work holds sending and receiving transducers in precise alignment to define fluid interrogation paths, while a simple spacer decouples each transducer from the frame. Different path lengths define disjoint reception windows which may be processed in real time by single channel electronics, and multiple pairs of transducers may be coupled in parallel to the channel.

In one decoupling embodiment, a specially-configured O-ring isolation mounting is interposed in the solid noise path to attenuate systemic noise. Different constructions utilize this isolation structure, and the transducer elements may themselves be secured by the O-rings, or the elements may be attached to structural members that are secured and isolated by O-rings. Particularly beneficial isolation properties are obtained by lightly sandwiching a mounting flange axially against or between rings of particular attenuating materials. The fluid which is to be sensed may be contained or constrained in a thin walled vessel or conduit, such as a metal foil bellows, which does not itself possess sufficient dimensional stability to define an accurate ultrasonic interrogation path, but which forms a suitable flow cell, and which has a wall thickness selected so that signal propagation in the wall is slower than the signal's sound speed in the fluid. A separate holder or framework then precisely positions and supports the transducers and aims them through the fluid in the thin-walled conduit. The bellows provides temporal isolation of the energy burst which is transmitted directly along the conduit, while the framework provides physical and dimensional rigidity, together with some acoustic isolation, which may be introduced by extended path, impedance mismatch, attenuating O-ring sandwich or a combination of these techniques. Extremely low impedance conduit materials, such as PVC pipe, may also be used to assure low speed propagation of the solid-borne signal.

Particular systems utilizing O-ring isolators of the present invention are compact, since the usual stand-offs, dampers and spatial isolators are not required. In particular, many transducers may be mounted on a single hole plug mount to perform multi-

path, multi-range or multidirectional ultrasonic interrogation or reflectometry, or multiple transducers may be mounted on arms, lattices or countersunk holes aimed along different axes and effectively isolated from each other. Simple systems consisting of multiple plug-, flange- or frame-mounted transducers may operate in conduits or open regions to provide measurement applications such as an anemometer, a device to measure flow, lift or circulation about a structure in a wind tunnel, a system to measure swirl in a conduit, or a single-opening stack or duct gas density or flow meter.

Liquid or gas flow systems using different legs of a thin-walled containment structure, or different length paths in a flowing fluid allow temporal separation of received signals, and include complex multi-measurement systems wherein one or more transducers are simultaneously energized to transmit along the paths of different lengths such that energy is received by a plurality of receiving transducers in several different time windows and plural reception signals are processed by a single channel of an instrument.

These and other features of the invention will be understood from the description below, taken together with figures illustrating various embodiments thereof.

Brief Description of the Drawings

Figures 1A and 1B show detail views of transducer mounting and mechanical isolation in an acoustic measurement assembly;

Figure 2A illustrates a method of ring spacing in the assembly of Figure 1A;

Figure 2B is a signal trace showing effective isolation in the flow cell of Figure 1A;

Figures 3 and 4 illustrate hybrid systems with separate acoustic and structural isolation sections;

Figure 5 illustrates transducer isolation with an O-ring sandwiched flange;

Figures 5A - 5D illustrate systems using O-ring isolation;

Figure 5E illustrates a self-referencing one-port system using transducer isolation;

Figure 6 illustrates signal isolation in a long, thin-walled flow cell of small diameter;

Figures 7 and 7A illustrate the transducers of Figure 5 - 5D in an unconfined measurement system;

Figures 7B-7D illustrate details of a related system for measuring circulation and flow velocity components;

Figures 8 and 8A illustrate a flange-mounted single-opening triple midradius path sensor;

Figure 9 illustrates another embodiment of a triple midradius circulation sensor;

Figures 10, 10A and 10B illustrate a wind tunnel circulation sensor;

Figures 11 and 11A illustrate a chordal circulation sensor in a contoured wind tunnel;

Figure 12 illustrates closed path integration to measure aerodynamic quantities for an ultrasonic measurement of lift;

Figures 12A and 12B illustrate different transducer mounts;

Figure 12C shows an electrically paralleled differential path measurement system;

Figure 13 and Figures 13A-13C show clamp-on chordal measurement systems;

Figure 13D illustrates a system with two clamp-on transducer assemblies which also takes axial and cross flow measurements;

Figure 13E illustrates chordal interrogation with external clamp-ons;

Figure 14 illustrates another temporally separated acoustic system;

Figure 15 illustrates a multiconduit system with many measurements electrically paralleled;

Figure 15A illustrates a single conduit measurement system with paralleled axial and cross flow measurements;

Figures 16 and 17 show systems using a multiplicity of scatter path signals;

Figure 18 shows a two conduit electrically paralleled system;

Figures 19, 19A and 19B illustrate a pressure sensing flow measurement system and special transducer assembly construction;

Figure 20 illustrates a complex system with different fluids in different conduits;

Figure 21 illustrates a fill-monitoring system for material in a hopper or storage tower;

Figure 22 illustrates an electrically paralleled system for simultaneously monitoring a flow cell and a bypass path;

Figure 23 shows a circulation measurement system; and

Figures 24A, 24B show arrangements for electrically paralleled measurements on rectilinear and prismatic, respectively, conduits or vessels.

Detailed Description

The present invention relates to signal isolation in acoustic measurement systems, and particularly to gas measurements. A range of construction details are described, for example in connection with Figure 15A of applicant's aforesaid International patent application, the text of which is hereby incorporated by reference in its entirety for a fuller description of the context and operation representative systems.

That publication describes a construction wherein a conduit or housing wall is made thin to propagate flexural waves at low speed, and massive rings are spaced along the wall to attenuate the propagating energy.

Figure 1A shows a further measurement system embodying principles of that patent. In Figure 1A, the path of interrogation is folded along a U-shaped channel. The bottom leg of the U-shape is substantially massive and includes two $\pi/4$ reflecting surfaces.

The side legs of the U-shape are thin-walled tubing, typically 1/4 mm thick, of stainless steel pipe material SS316, welded at each end into more massive sections. Massive rings are clamped at intervals along the tubing and these are collars, corresponding to the rings of the aforesaid International application and are preferably alternately rotated $\pi/2$ to stagger their split ring slots and to interrupt the acoustic path along the thin-wall path as much as possible.

Each transducer assembly in Figure 1A includes a quarter-wave matcher 3 epoxied directly to the membrane (corresponding to the diaphragm 4 in Figure 15A of the aforesaid PCT application). This holds the membrane in place even under evacuation of the cell. The transducer housing is packed to resist high gas pressure in the cell, although the gland and lock nut are of somewhat different design than in the aforesaid publication. A backup seal consisting of an attenuating O-ring of silicone or fluorosilicone may be captured between the transducer housing and the nearby cylindrical wall. In MOCVD (metalorganic chemical vapor deposition) applications, it is common practice to maintain the temperature of measurement cells by immersing them in a water bath whose temperature is kept constant to the order of 0.1 degree C or better. When the cell of Figure 1A is to be immersed in such a bath, a plastic wrap is used to prevent water from acoustically short circuiting the isolation rings. The plastic may be a shrink wrap plastic.

As described in the earlier aforementioned PCT document, the rings may be employed for isolation in embodiments wherein the transducer housing itself contains the isolation structure. In that case, the transducer housing includes a thin-walled stand-off, and located within the thin-walled transducer housing are a plurality of massive titanium steel or carbon steel rings 60a, 60b, 60c which are press-fit in position spaced apart slightly from each other by interposing silicone O-rings of approximately 1.5 mm cross section (Figure 2A). The massive rings may be welded to the housing to secure them in place.

Applicant has found this construction to provide a high level of acoustic isolation. Figure 2B hows an actual test result for the U-shaped cell of Figure 1A, namely, a received signal propagated through air in an imperfect isolator conduit, indicating the level of crosstalk (region A) that, ideally, would be absent, and the gas borne transmitted signal (region B), for which the SNR is on the order of 100:1.

The foregoing examples illustrate solid body attenuators in which elastic elements -- alternate metal rings and thin shells in series -- attenuate noise transmission.

It is the primary purpose of this invention to provide a relatively simple isolation structure in which O-rings made of attenuating material are lightly sandwiched with

low contact force about a steel or highly elastic flange or even a strong plastic solid body. Furthermore, hybrid constructions are possible wherein a conduit or gas measurement chamber is formed of a very thin and structurally indefinite wall -- for example a metal bellows -- while a separate frame or outer housing provides dimensional precision and structural rigidity to secure the transducers in defined positions. Each of these constructions will be further discussed below.

Figure 3 shows a hybrid system 300 comprised of two major elements, a thin walled containment vessel 250 and a rigid frame 280. Frame 280 consists of a first yoke 284a fitted to one end of the vessel 250, and a second yoke 284b fitted to the other end of vessel 250, with the two yokes being rigidly spaced apart by an elongated rail or body 282. A transducer 260 is fitted into each yoke and directed along the axis of the containment vessel 250. Vessel 250 is a limp and flexible tube, preferably corrugated, and having a very thin wall such that the product of its thickness with the signal frequency (corresponding to the lowest order flexural wave (a_0) speed in the material) is low, e.g., below 1 MHz·mm. This assures that the noise in vessel 250 travels more slowly than the gas-carried signal, so that the gas measurement signal may be detected before vessel-borne noise arrives.

As illustrated in Figure 3, each of the solid frame members constituting a yoke 284a, 284b is secured to the rail 282 by being clamped between a first and second O-ring 291, 293, with rigid plates or collars 295, 296 tightened against them to securely fix the position of the yoke. The corrugated bellows 250 is rigidly attached to the yoke at each end, preferably by brazing or with a sealing ferrule, gasket or sealing material. Suitable flexible tube assemblies are available from The Cajon Company, a division of The Swagelok Company, of Macedonia, Ohio as their 321SS flexible stainless steel tubing, and are available with glass or weldable metal end fittings (cuffs). These bellows are suitable for relatively low pressure gas measurement applications. Preferably a system for general use in the chemical process industries and for many metalorganic chemical vapor deposition processes would utilize a bellows or corrugated tube of 316 stainless steel, rather than the common commercial 321SS product.

The selection of O-ring material requires some care. Preferably the O-rings are formed of material which is acoustically attenuating and suitable for the intended chemical and thermal environment. Applicant has found silicone, fluorosilicone, neoprene and Buna-N to be suitable materials, with fluorosilicones offering excellent resistance to high temperatures and hydrocarbons. Several common O-ring materials, notably Teflon and Viton, were found to provide very poor isolation and to be unsuitable. The O-ring thickness also requires careful selection. For example, on the assembly of Figure 3, with O-rings fitted about a ten millimeter diameter rod 282, a silicone O-ring 2.3 mm thick provided best

isolation, whereas a ring twice as thick of Neoprene or Buna-N was required. In each case, the ring was tightened adequately to obtain rigidity, but to a less compressed state than is customary when O-rings are used for sealing. For example, a compression of well under forty percent, and preferably about ten percent is suitable, with care being taken that the solid frame 284 and mounting plates 295, 296 do not contact each other. A thin wire or protrusion may be brazed to the surface of the plates 295, 296 to act as limit stops. Other isolation means as described above are also shown applied to the rail 282 to further cut down on acoustic short circuiting. For example, as shown in the embodiment of Figure 3, a plurality of massive damping rings 298 are spaced along the rail 282.

Figure 4 shows a related O-ring isolation construction in which a dimensionally stable mounting plate is isolated by O-rings from a pair of end posts that hold the bellows.

As was the case with the massive damping rings, this O-ring isolation structure may also be applied directly to the transducers.

Figure 5 shows such a construction, wherein a transducer 310 including a crystal 311 and suitable coupling and diaphragm are mounted in a small cartridge-like housing or case 315 having a flange 316. The case 315 is fitted into a bore 320 in a conduit or chamber, with the flange sandwiched between a pair of O-rings 321a, 321b. A gland or packing nut 322 tightens the assembly down, allowing secure fixation and slight positional adjustment along the transducer axis. In this manner the transducer itself is isolated from the solid body of the fluid-containing structure. As shown in this illustration, this isolation mount is particularly compact, allowing two or more transducers to be placed adjacent to each other in separate bores in a single solid body 325, which may, for example be the wall of a thick-walled pipe, a plug, or a pipe flange or flange cover as illustrated. The lock nuts, if used, are tightened after the gland is tightened.

The illustrated bores 320 are shown at normal incidence. Advantageously, applicant has found that with the degree of acoustic isolation provided by this O-ring mounting, sufficiently well-defined signals are obtained to take flow measurements in fluids such as gases in various ducts or conduits that are known in the trade as vents, pipes, headers and stacks, by using transducers spaced apart at a distance L appreciably smaller than the stack or conduit diameter, and mounted at normal or near-normal incidence on a plug or cap. For example, using a small reflector R in the stack or conduit as shown in Figure 5A a downstream transducer 310b may catch the reflected signal transmitted by an upstream transducer, 310a, both mounted at normal incidence in a single plug or corner plate of small dimension. In smaller conduits the transducers may be mounted in separate bores directly in the conduit wall, or in a single clamp-on mounting block positioned over a wall opening or

over a thinned wall position, while remaining substantially isolated from each other. In preferred one-port installations, the measurement of flow averaged over an interrogation path out to the reflector and back, would very nearly equal the area averaged flow velocity in the conduit and would be relatively insensitive to Reynolds Number Re at least for fully developed turbulent flow profiles. The examples in Figure 5A have this property.

More complex arrangements of transducers in a single conduit, or with a single measurement instrument are thus possible. For example, as illustrated in Figure 5B, each channel of a four-channel driver/intervalometer measuring instrument 400 such as a Panametrics Model 6068 or GP68 may be attached, without switching, to each of the four sending and receiving transducers (A_1-A_4 and B_1-B_4) in four pipes, with the transducers in each pipe arranged to provide four different length paths with the transit time differences each greater than the ring-down time, so that the signals may be received in different time intervals in a single channel from each path of a given pipe with the transducers connected in parallel. Further systems of this type are discussed below, in connection with Figures 13-14.

This O-ring isolation mounting is versatile, and in addition to use in a crystal housing or a rigidizing external frame as discussed above, may be applied to a buffer rod or standoff located between a transducer crystal and an impedance matching launching structure for gas interrogation. Figure 5C shows such a configuration, wherein a transducer crystal 422 is coupled by a buffer rod 425 to a quarter wave coupling block 423, and a flange 424 located at approximately the rod's center of gravity is provided for isolation mounting between O-rings. This allows the crystal to be supported in relative thermal isolation as well as acoustic isolation, many wavelengths, and up to five or more pipe diameters, away from the conduit and fluid.

In Figure 5E there is shown another one-port nozzle assembly 510, similar in some respects to that shown in Figure 5A for interrogation perpendicular to a conduit, duct or stack. In Figure 5E, however, there is a reference reflector 512 adjustably positioned very near the inside surface of the duct 600 in which flow is to be measured. This reflector provides a reference echo whose transit time provides a correction to transit times in the freestream across the duct, as is increasingly important if temperature gradients are present. The reference echo amplitude is proportional to the gas acoustic impedance, as mentioned elsewhere herein, and so can be processed to yield gas pressure or gas density. The amplitude of this echo in other circumstances can be used to monitor the cleanliness and integrity of the transducer system. Figure 5E also shows two waveguiding tubes or pipes 520a, 520b, each concentric with the axis of its respective transducer, and extending essentially to the freestream. This construction avoids beamspread in the nozzle and also avoids most of the turbulence that might otherwise attenuate the signals before they even

emerge from the nozzle into the freestream. The waveguiding tubes each have a slot 525a, 525b that allows a predetermined small fraction of the energy within each tube to leak intentionally along a vee path to the reference reflector and then be received in the other tube through a similar slot. The transducers, when installed in their respective transducer ports and operated at wavelengths just a small submultiple of the transducer aperture, e.g., 25, 50 or 100 kHz, approximately, for apertures about 15 to 30 mm, lead to sufficient beamspread to obtain the reference information using the vee path illustrated, and to also obtain flow information along the vee path shown in broken fashion in the duct itself. The schematic of the waveforms associated with this type of reference and freestream interrogations represents the important reference and flow echoes at A and B, in the simplified waveform sketch below the drawing.

Returning now briefly to the first discussed isolation structure, that of alternating masses, a further embodiment with variations is shown in Figure 6. This system 450 involves a measuring path of length L with the signal path defined by reflector plates 451 to direct ultrasonic signals along the flow axis, with a plurality of massive collars 455 placed about the conduit, and/or thick sleeves 458 placed within the conduit. The sleeves may be of differing thickness, hence inner diameter, in order to better break up reflections from the interior of the duct. A spiral coil 430, which may be of constant, progressive or irregular pitch scatters in the conduit wall any energy reflected against the wall from the fluid, so that an essentially purely axial wave propagates in the fluid. This arrangement effectively filters or sharpens the signal trace by eliminating higher modes and spurious multi-path vibrations traveling with the ultrasonic signal but not propagating axially.

While the above descriptions have focused on the isolation achieved between the ends of a vessel or conduit on the one hand, or a transducer and its surrounding vessel or conduit on the other hand, the described isolation structures may also be applied to free-standing, externally-attached or unconfined transducers and measurement systems. In that case, a simple counterbored yoke or bracket 440 as shown in Figure 5D may be mounted on a frame, rod, or existing structure such as a beam or culvert, to direct its signals into, or receive signals from, surrounding air.

One application of such point-like gas-exciting transducers is an ultrasonic anemometer 450, shown in Figures 7 and 7a. Three acoustically isolated transducers 451, 452, 453 are held by a rigid, non-rotating frame 456 having a body which directs the transducers along three independent pathways a, b, c having x, y, and z components, to receiving transducers 451, 452, 453 positioned to sense the signal from its sending transducer, providing a readily derived contra-propagation transit time interval, or other measurement, from which wind direction or speed components are calculated. O-ring

isolators are shown in the detailed view Figure 7A of one pair of transducers. By arranging that pathways a, b and c differ sufficiently, all three pathways may be interrogated at once by paralleling their respective transducers. As wind gusts can be quite rapid, the fast response afforded by interrogating all three components of wind essentially simultaneously yields more meaningful results than if there were substantial delays or uncertainties in synchronization for wind components sensed seconds apart, i.e., not simultaneously.

One particular application of this gas transducer signal technology is the provision of closed path signal loops, with the path defined by one or more transducers and/or reflectors, to measure a physical quantity corresponding to a path integral of interest. Figures 8 and 8A show a face view and an edge view, respectively, of a pipe flange 500 incorporating isolated transducers such as the transducers 310 of Figure 5D.

A pair of transducer mounting bores 505, 506 are formed in the flange 500 directed at angles to cross at a single opening 510 in the inner circumferential edge of the annular flange, which is illustratively sized to be clamped or bolted as a measurement collar in a ten inch steel pipe, either between flanged sections of pipe, or alternatively slid over a section of pipe with an opening or thinned wall formed in the pipe and aligned below the opening 510. The transducer path is aimed along a midradius path, tangent to an axially centered cylinder of radius one-half the pipe radius, so that the ultrasonic beam is reflected twice from the inner wall of the conduit, forming an inscribed equilateral triangle path between sending transducer 505 and receiving transducer 506. The signal path transit time, together with the known geometry of the flange, thus provides a closed loop path integral of V•ds on a three-leg path surrounding the pipe axis. This provides a direct measure of the circulation Γ_z about the conduit axis. The two transducers are located adjacent each other in the solid flange. In the illustrated 10-inch flange, the circulation path is $L_c = 15 \times 1.732$ inches and the total gas path is approximately $P = L + 3.26$ inches. To prevent gas-borne crosstalk in an arrangement where the two ports join as one, one must use a sufficiently high ultrasonic frequency, or may thread or otherwise roughen or modify the ports at regions 510a, 510b from the idealized geometry presented for illustrative purposes so that scatter from the first angled port does not coherently get up into the adjacent second port by way of their common passageway.

Inasmuch as the calculation of Γ_z for this path requires the evaluation of $c^2\Delta t/2$, where c = sound speed, it is clear that the "Flowmeter" can calculate other characteristics of the fluid that depend on c. Temperature T is one such characteristic, since for a gas, T is proportional to c^2. For many liquids, T may be calculated as a linear function of the sound speed, T = Ac+B, where A and B are constants.

Figure 9 shows another embodiment of a device 520 for taking a midradius path measurement of circulation about the pipe axis. In this embodiment, a pair of isolated and angled transducers are mounted in an external block, directed along chordal paths through a pipe opening. By alternating propagation along clockwise and counterclockwise paths a measure of the magnitude of swirl or circulation Γ_Z about the axis is obtained.

In other applications, isolation transducers may be mounted with separate reflector elements or opposed transducers to define different closed paths, or approximately planar closed paths for determining particular characteristics or deriving other components of fluid circulation.

Figure 10 shows another closed path sensor configuration 600, illustratively for sensing circulation Γ_X about a test object 601 located in a wind tunnel. A pair of transducers 605, 606 are directed at a beam splitting reflector 610 (or a pair of single beam reflectors) that, together with reflectors 611a, 611b, ... 611n form a closed polygonal acoustic path around the object 601 between the two transducers. The transducer separation is selected to be small compared to the dimensions of the tunnel and the test object, so that the path is effectively a closed path. In lieu of the reflectors, separate transducers may define the endpoints of each segment, in which case more signal processing is required. The reflectors preferably are not located too close to the walls, in order to avoid transit time ambiguity and inaccuracy that might arise due to thermal or flow gradients in the boundary layer.

As shown in Figure 10A, a pair of reflectors located in adjacent planes may be used instead of beam splitter 610 to define a full contour around the test object (so that $\Delta z = 0$). Figure 10B is an end view, showing the vaned nature of the reflectors, which define measurement paths in closely adjacent planes while allowing normal airflow along the wind tunnel axis in the plane of interest.

In another embodiment shown in Figure 11, by employing a spherical or cylindrical test chamber 550 which is smoothly enlarged from the nominal tunnel inlet and outlet, a single opening 555 (shown in detail in Figure 11A) allows a triple midradius interrogation path using the chamber wall as a signal reflector. This provides a small number of paths, which are well centered in the air stream and require no protruding reflectors. As shown in Figure 11A, the chamber opening may have a screen or mesh 556 along the interior wall contour to preserve smooth aerodynamic flow properties.

Figure 12 illustrates in schema possible path integral measurements performed in this way. The circulation Γ_X about a model extending in the x direction may be pieced together from path measurements made in parallel but slightly offset planes. For example,

under reasonable assumptions of continuity, the integration path ABCD may be approximated with the segments A"B" and C"D" from one plane, and B'C' and D'A' from an adjacent plane, with both the " and ' planes located adjacent to the plane of interest. This minimizes the aerodynamic effects of the transducers or reflectors on flow in the plane of interest.

Similar polygonal paths may be set up ahead of the test object to determine the swirl velocity at the inlet, and the circulation Γ_Z about the z axis. Thus, all functions necessary to compute lift may be directly measured by ultrasonic signal interrogation and simple signal processing. Since lift = $\rho V_Z \Gamma_X$, and (a) the amplitude of the received signal yields the gas density ρ; (b) conventional contrapropagation measurements yield V_Z; and (c) clockwise and counterclockwise path measurements yield Γ_X, the product of these three quantities yields the sought lift.

Referring still to Figure 12, it will be understood that in order to utilize the primed and double primed planes that are close enough in proximity that measurements in these planes closely approximate the closed path integral required for a circulation measurement, one must be able to isolate closely spaced transducers such as those at A' and A", B' and B", etc.

An alternate approximation to the closed path integral can also be obtained using a corner transducer assembly as shown in Figure 12A. In this design, a pair of transducers 310 are sealed and held in place with their axes both in one plane, using the O-ring flange sandwich method. The housing 319 for the two transducers is itself secured inside a wind tunnel, typically at four places in the yz plane to measure circulation about the x axis, that is, about a model oriented along the x axis. Each transducer is held as in Figure 5.

The ability to isolate by the O-ring flange sandwich method, two closely spaced transducers is also utilized in the blocklike housing 330 of Figure 12B. This block is designed to be welded or otherwise sealably secured to a standard pipe.

The advantage of this block over prior art constructions is that the spacing of the transducers can be controlled more precisely than if one mounts separate angled coupling or nozzles onto the pipe. Precise control of spacing is retained even if the holes in the pipe are oversized, undersized or elongated, or have their axes normal to the pipe wall. Previously, the separate blocks were often selected as the standard design approach, in order to achieve isolation.

As one reduces the frequency f at which the flow or other gas characteristic is measured, there is generally more beam spread and a greater tendency for signals to propagate over spurious (unwanted) gas paths. The remedies for this problem include judicious use of scatterers on surfaces from which no reflection is wanted. The use of a spiral or inserted sleeve was mentioned earlier. Other remedies include anechoically roughening or corrugating portions of the offending surface, or threading the surface if it is cylindrical and conveniently threaded by tapping or inserting a "threadsert," which is a form of spiraled insert normally used to secure screws.

In the plastic square- or rectangularly-channeled flowcell of Figure 12C, the plastic wall is periodically corrugated, as shown; so too is the cover plate (not shown). The two cell sections connected in series illustrates a configuration for switchless fast response flow metering, in which the system configuration greatly simplifies the required electronics.

The foregoing techniques of providing acoustic path isolation or, for longer pathways, temporal isolation of crosstalk allow one to implement systems wherein an ultrasonic driver/intervalometer measurement instrument dependably distinguishes the signals of interest.

In accordance with another aspect of the invention discussed above in relation to Figure 5B, elements of a system are arranged so that plural transmitting and receiving transducers are connected parallel to a single channel of such an instrument, the signals being received in disjoint subintervals or timing windows so that transducer switching or multiplexing are not needed. Representative embodiments will be discussed in connection with multi-path sensing situations, such as wind-tunnel swirl measurements, triple midradius chordal measurements, axial- and cross-flow measurements, and the like.

Various differential-delay paths will be illustrated below, wherein the time interval windows for each path are spaced to avoid contributions in any window from transducer ringdown or path reverberations from a shorter path. In accordance with some embodiments of this aspect of the invention, the spacings of transducers are set so that received signals are centered in a sequence of windows at time intervals proportional to a sequence of prime numbers, thus avoiding a common factor which might allow interfering reverberations into a sampling interval. For example, in a four path Gaussian Quadrature flow cell, one may arrange to have each of the four path signals arrive in separate windows analogous to the four separate windows W_1, W_2, W_3 and W_4 of Figure 5B. As a numerical example, for a 10-inch diameter steel pipe containing water, for which an appropriate interrogation frequency would be 1 MHz with a well-damped transducer that quiets down in a ringdown time $t_{rd} = 10\mu s$ or less, i.e., ten cycles or less, the Gauss-Chebyshev paths could

each lie in a different plane, such that P_1, the shortest path, in inches, would be the first prime number larger than 10 (that is, $P_1 = 11$ inches) and the other paths would have path lengths $P_2 = 13$ inches, $P_3 = 17$ inches and $P_4 = 19$ inches. At room temperature, the corresponding transit time would be $t_1 = 176\ \mu s$, $t_2 = 208 \mu s$, $t_3 = 272 \mu s$ and $t_4 = 304 \mu s$. As each of these "prime number paths" differ from one another by at least 2 inches, the transit time reception window centers are separated by over $3t_{rd}$ and no transit time t_i is an integer multiple of any other time, by virtue of the prime number sequence. This substantially avoids overlap of transducer and other path reverberations.

Gas transducers for use at lower frequency, e.g. 100 kHz or below, if made of rigid high-impedance crystals as shown in Figure 1B, tend to ring on the order of 50 to 100 cycles even if damped by soft attenuative potting agents like silicone rubber. Thus, if the period T_x of the transducer's natural frequency f is $T_x = 1/f = 10 \mu s$, the ringdown time t_{rd} for 50 cycles of ringing is (50) (10 μs) = 500μs = (0.5) millisecond, and twice that, or 1 millisecond, for 100 cycles of ringing at $f = 100$ kHz. Air paths corresponding to these transducer ringdown times are about 0.5 to 1 foot. Hence, a sequence of "prime number air paths" for transducers that ring for 100 cycles could be 3 feet, 5 feet, 7 feet, and 11 feet. Such ranges are within the practical capability of 100 kHz commercially-available ultrasonic equipment such as described, for example, by the applicant and colleagues at the EPRI Heat Rate Improvement Conference, November 1992. At $f = 50$ kHz, there is less attenuation in air, so the range increases to over 50 feet, allowing one to employ an even greater number of prime number air paths, e.g., 13, 17, 19, 23, 29, . . . 47 feet. Any three of such prime number air paths may be used to define the spacing of transducer pairs for a three-component sonic anemometer having electrically-paralleled paths, as shown in Figure 7.

Figure 7B shows such an arrangement of eighteen transducers mounted to perform substantially simultaneous acoustic interrogation along three independent closed loop signal paths with minimal processing instrumentation. Each contour is a right scalene triangle having 3-4-5 proportions, and each triangle is disposed in a different orthogonal plane and has its shortest leg longer than the hypotenuse of the next smaller triangle. A pair of transducers at each vertex of a triangle are aimed at the other two vertices of the triangle, so that the difference in transit time around the triangle is obtained from its six transducers, and represents the component of circulation Γ_x, Γ_y, or Γ_z about the axis perpendicular to the plane of the triangle. Figure 7C illustrates the channel allocation of the transducers A-R, which are connected as two sets of nine transducers in parallel to the driver/intervalometer. Figure 7D plots the disjoint timing windows of the received path length signals. The illustrated configuration is for wind measuring swirlometer which requires only a thin frame to secure the transducers in the surrounding airstream. All hypotenuse paths are oriented differently (skewed), and in the open airstream reverberations should pose no problems, so it

is not necessary to provide for "relatively prime" reception intervals of the type discussed above. The different x-, y-, and z- paths also yield V_x, V_y and V_z measurements. The invention also contemplates allocating a separate processing channel to each circulation measurement, with the same size frame and right scalene triangle used for each set of transducers, in a more compact embodiment.

In each of these embodiments, implementation of the invention contemplates the provision of well-aligned corner transducers, such as indicated schematically by the Γ_y transducer pairs IH, GL and JK of Figure 7B, which are preferably implemented in modular blocks, similar in construction to that of Figure 12A, below, each having a pair of precisely-aligned bores for accommodating transducers directed along the bore axes. Advantageously, the blocks are either right-angle blocks, or else have their bores oriented at an angle such as thirty-seven, or fifty-three degrees, oriented precisely for either rectangular transducer arrays, or arrays laid out at one of the vertices of a 3-4-5 triangle. Alternatively, each corner block may comprise two blocks hinged together, each holding one transducer, so that their transmission angles may be adjusted in the field to a desired geometry and the block then clamped in that position. Thus, by arranging for temporally disjoint signal reception windows in this manner, a number of transducers may provide parallel inputs to a single processor, and achieve complex measurements.

By way of general further background, modern ultrasonic systems typically operate with a single instrument box of which the circuitry includes, on the one hand, a driver portion for energizing a transmitting transducer with a signal burst, and a digitally operated signal receiver/analysis portion which is synchronized to the drive burst and processes the signal received by a receiving transducer. Reference is made to commonly-owned United States Patent No. 4,787,252 for a description of the digitally-implemented signal sampling, correlation and time- or frequency-domain analyses which may be effected by such instruments. For example, the receiver/processor may sample and digitize the voltage appearing across a receiving transducer several hundred times during a several millisecond measurement interval, may perform signal conditioning, and may determine transit time differentials, measures of signal quality and other system data. In prior art systems, a processing channel may be intermittently connected to several different receiving transducers by switching circuitry to make measurements on different pipes, or more usually a multichannel instrument has one processing channel connected to each receiving transducer. This may require the use of special interfaces and recording devices to combine or display the result of the separate measurements when they form parts of a single process, and typically this results in an inefficient use of the limited bandwidth of the highly specialized receiver/processor.

In accordance with a principal aspect of the present invention, receiving transducers are connected in parallel to a single processing channel, and plural received signals are processed by the digital analyzer in sampling intervals that are separated due to transmission path delays which are preferably greater than ring down characteristics of the sensors involved. This construction is especially useful for performing closed path circulation or swirl measurements, and measurements in a highly constrained environment, of the type shown in Figures 7B and 8-12, where differing length path legs may be selected to allow one instrument to measure all paths in sub-intervals of a single short time.

The instrument hence can acquire all the data necessary for it to compute flow and other fluid characteristics in a short time
$T_c < n\ T_f$, where T_f is the time of signal travel in the fluid, and n is less than ten, and preferably between one and three. The processor may complete its processing activity in under one millisecond, so for the various sensing configurations described, all signal acquisition and processing is essentially completed within one millisecond of the time it takes for the acoustic signal to propagate along the longest sensing path. Shorter path signals preferably are processed earlier. Thus, all measurements are performed within an interval substantially equal to or shorter than the longest transit time. The electrically paralleled construction is also useful in other flow measurements, such as the device of Figure 12C, wherein the long multiply-reflected path results in separate arrival times at the two receivers due to differential retardation of the signal. Other embodiments are discussed below wherein reflected, scattered or delayed signals arriving at different intervals provide enhanced measurements.

Returning briefly to the system shown in Figure 12 for measuring swirl and circulation, the closed contours ABCD or EFGH may be any closed paths in the YZ or XY planes, respectively. Preferably, however, they are arranged so that the paths AB, CD are different lengths than BC, DA, by an amount such that the transit time difference for waves simultaneously launched at one corner, is greater than the signal sampling interval of the receiving circuit, and such that the transit time along the shortest path (say BC) is greater than the ringdown time of a transducer interrogating that path. With this constraint on path length, both transducers of a corner transducer Figure 12A, or separate pairs of sending and receiving transducers at one corner, may be simultaneously actuated while a single channel receiver processes the signal received at two adjacent corners. Applicant refers to such a measurement system as having a differential path and electrically parallel transducers. As compared to conventional systems, such configuration dispenses with complex multiplexing or synchronization circuitry, and uses the internal measurement software defined processing intervals and sample definition. As discussed more fully below, this configuration reduces required measurement channels.

Rather than a closed path integral as illustrated in Figures 7B, 8, 11 and 12, a good measure of swirl may be obtained by interrogating a chordal segment in both clockwise and counterclockwise directions and then scaling the time difference Δt to approximate the swirl. The circulation of a fluid flowing along a conduit, given by the closed integral of $\mathbf{V} \cdot ds$ is approximated by
$1.5c^2\Delta t$, where Δt is the time difference of signal propagation in two opposing directions along a chord which is near to a midradius chord.

As with the other embodiments, these approximations may be performed at different stations along a flow, or in separate conduits at the same time, by using electrically paralleled differential path configurations. These configurations are useful for slower soundspeed interrogations, in which adequate temporal separation is achievable, such as in gases interrogated with wetted transducers. In such applications, single- or double-opening chordal interrogation may be performed using clamp-on transducer assemblies, as shown for example in Figure 13.

Figure 13 shows a cross-section through a large pipe or conduit 501 in a sensing system 500 of this type. A multipiece clamp assembly 504a, 504b, such as is commonly used as a wrought pipe clamp or extension pipe or riser clamp, is modified to have transducer mounts formed thereon, or more precisely welded to blocks thereon or clamped thereto in the positions indicated. A first pair of two transducers 510a, 512a attach to wedges 510, 512 welded to the clamp body. Both of these transducers are attached to the same half of the clamp 504b, and are oriented at an angle to launch and receive signals along a midradius chord through fluid flowing through the pipe. Their mounting angle is selected in accordance with the sound speed of the intended fluid, taking account of pipe diameter, wall thickness and refractive effects, as would be understood by a person skilled in the art. Another transducer 514 is shown mounted in the clamp at an angle for interrogating along a different path to an opposed transducer further along the axis of the pipe on the other side to take axial flow measurements. Finally, a pair of transducer mountings are shown 515, 516 angled over an opening 520 in the pipe and directed for taking closed path contrapropagation signal measurements using internal reflections from the pipe body, similar to the closed chordal path arrangement shown in Figure 8, but in this case, the clamp is a simple strap metal clamp rather than a large precise casting or spool piece. Corresponding to opening 520 in the pipe is an oblong hole through the clamp. This hole may be threaded at its edges to eliminate any significant coherent scattering or crosstalk between the two closely spaced transducers 515, 516. In general, these latter two transducers and their closed path chordal interrogation are useful for gases, such as air. The clamp assembly may be fitted with either these triple midradius chordal transducers, or with the clamp-on transducers 510, 512 suitable for

interrogating liquids. As shown in the detail views included in this Figure, the clamp-on transducers attach to a wedge that extends through the clamp 504b and is pressed against the pipe wall to form acoustic contact as the clamp is tightened down. These rod wedges may also be wetted with a couplant.

Figure 13A shows a clamp-on swirl sensor variation of this system. In this embodiment, two pipe clamp halves 505a, 505b each have a wedge mounted thereon in a corresponding or identical position, so that when mounted together to fully surround the pipe, they lie at or near opposite ends of a diameter of the pipe. The wedge is oriented without particular regard to the liquid in the conduit, whose sound speed is c_3, so that wave energy launched by the wedge may internally refract, spread by diffraction and reflect numerous times within the wall of the pipe as shown in the Figures. It exits the conduit wall numerous times over a circumferentially-elongated region and proceeds to the opposite transducer. In this case, although the contrapropagation chords are not identical, the symmetry assures that the Δt remains well defined and essentially the same for numerous chords and the positions of the sensors are thus not critical. This allows the system to be implemented by manufacturing clamp halves with a single transducer wedge mounting, despite application to liquids of differing c_3's. Returning briefly to Figure 13, it further bears note that in the gas measurement environment, leaking waves may propagate between transducers creating a certain degree of crosstalk, the amplitude of which will depend on the gas pressure. The strap may have a hollow section to accommodate such leakage and provide a gas path between transducers that can be independently monitored for noise level to determine operating pressure. Note that to detect the presence of swirl, it suffices to determine if Δt is nonzero. Therefore, even if all chords do not yield identical Δt, the Δt's will be of like sign and thus be additive if swirl is nonzero, allowing a simple and reliable determination of whether swirl is present.

Figure 13E shows several ways of theoretically achieving a swirl-sensing chord exactly along a midradius path. In this drawing, the pipe has an internal radius R, and external radius R_{OD}, and a wall thickness $w = R_{OD} - R$. The Figure is drawn with relative proportions for a medium-size conduit, and the locations of the outer surface (hence the wall thickness relative to diameter) for a large diameter or small diameter pipe are indicated by ghost lines OD1 and OD2, respectively. A midradius chord is designated MR, while the normal line at its intercept with the inner wall of the conduit is designated N. A pipe diameter D is parallel to the midradius chord MR. The pipe is presumed filled with water having a sound speed c = 1500 m/s. By way of examples, for pipe materials such as PTFE, Cd, Cu and Ni, having published sound speeds as listed in the table in that Figure, applicant has calculated angles of incidence θ_2 in the pipe wall and location EP of the signal entry point that is necessary for each material in order to refract along the midradius chord parallel

to the diameter and spaced therefrom by R/2. The location of each entry point on the pipe OD in that Figure, for the given pipe wall thickness w varies for each material. Note that for PTFE (Teflon), whose longitudinal wave velocity is less than that of water, the entry point is slightly above the midradius' extension at the pipe's outer surface. For Cd, whose c_s equals c in water, 1500 m/s, the entry point is exactly on the extension of the midradius chord. For more common metals, such as Cu and Ni, the entry point is below the midradius extension, and for Ni it is exactly on the diameter D.

It will be appreciated that this entry on the diameter would appear to be a very special case, and the result would generally differ when considering a pipe of slightly larger or smaller OD, or a pipe of material having a different sound speed than 2960 m/s, or a pipe in which the liquid therein has a sound speed ≠ 1500 m/s. However, the methodology for identifying transducer placement to effect interrogation along a desired chord is quite general, and similar remarks apply for chordal interrogations of swirl along chords other than the midradius. Based on this type of analysis, applicant concludes that the preferred entry point, for a horizontal chord to be interrogated both clockwise (CW) and counterclockwise (CCW), will typically be at least twice the pipe wall thickness below the swirl sensing chord, and may be up to about ten times the wall thickness below that chord. For typical steel, stainless steel and aluminum pipes containing water, Snell's Law will limit the swirl sensing chord to a position slightly closer to the center than the midradius chord. This leads to a rule of thumb, that the swirl sensing transducers be positioned 2w to 12w below the R/2 chordal intercept, for those combinations. A corollary rule of thumb found by applicant, is that if the first rule in combination with pipe dimensions happens to straddle the pipe diameter, then the diameter is a preferred entry point. This corollary rule of thumb recognizes the ease of coupling across the diameter at diametrically opposed points, using for example quick-acting clamps, and furthermore, the diametrically opposed points of entry for swirl sensing are also the preferred points of entry for sensing cross-flow. Hence, the same transducer block can accommodate both swirl and cross-flow sensing transducer piezoelements.

Figure 13B shows a vertical elevation, partly in section taken parallel to the axis of the conduit shown in Figure 13. In this embodiment, two strap assemblies 504, 505 are placed around the conduit, spaced apart along the axis of airflow, and arranged such that a slanted transducer 514a (similar in orientation to transducer 514 of Figure 13 but in the present instance, tilted axially) is aimed along the axially slanted path 525 to a similar transducer 514b mounted obliquely on the other strap clamp 505. As illustrated, the oblique clamp-to-clamp transducer mountings are formed in large three-axis mounting blocks 520, each of which also has two chordally directed transducers C and D mounted like transducers 515, 516 in Figure 13 to take chordal measurements along a closed path in the plane of the clamp. A single channel contrapropagation flow meter 530 is attached to the transducers.

Illustratively, designating clamp transducer 514a as transducer A and 514b as transducer B, the flow meter may be attached to transmit simultaneously in parallel on transducers A and C and process the signals received from transducers B and D. The oblique path 525 is set at 30 degrees from the vertical, making the path length 2.3 times the radius. The sum of the three midradius chordal paths between transducers C and D is approximately 5.2 times the radius, assuring that the single channel receives signals from transducers B and D in separate time intervals, differing by a time greater than the ring down time of the transducers. Transmission and reception are switched in ping-pong fashion yielding an upstream/downstream difference giving the flow velocity and a clockwise/counterclockwise difference giving the vortex circulation in the conduit.

In Figure 13B, the right-hand strap is also fitted with a vertically-extending buffer tube 514b at the top of which is depicted a first cross-flow transducer E. Cross-flow transducer E communicates across the diameter to second cross-flow transducer F mounted in the lower block 520. For air cross-flow measurements at ordinary pressures, it is necessary to make a hole through the strap and pipe wall so that the ultrasonic beam from transducer E can efficiently enter the air within the pipe. Contrapropagation measurements from E to F and then from F back to E yield the cross-flow velocity V_X. The buffer tube 514b is made along enough so that the cross-flow interrogation signals arrive long enough after the swirl signals as illustrated in Figure 13B, or between the axial and swirl signals, ringdown permitting.

Figure 13C shows a detailed view of the three-axis mounting blocks 520 of Figure 13B, with threaded bores for the transducers C, D and 514a of that Figure. Transducers C and D are offset $\pm \pi/6$ from the normal in a plane perpendicular to the pipe axis, while transducer 514a mounts in a bore directed $\pi/6$ across that plane along the axial direction.

The tapped hole centered on the normal n in Figure 13C accommodates one of the cross-flow transducers, namely cross-flow transducer F shown in Figure 13B. This transducer communicates through the same hole in the pipe as do the swirl and axial flow transducers. For a corresponding system for liquid application, where simple clamp-on interrogation is practical, the cross-flow transducers would be clamped normal to the pipe on opposite sides. In the clamp-on case, a preferred clamp-on wedge design provides in one module both swirl-sensing and cross-flow sensing piezoelements. However, pipe diameter, material and wall thickness will sometimes preclude a practical combination of swirl sensing and cross-flow sensing in one small module owing to lack of a path length solution that would yield disjoint reception windows as discussed above.

Another method of measuring cross flow is illustrated in a schematic end view, Figure 13D, showing a conduit wherein sending and receiving transducers A,B are mounted next to each other on the same side of the conduit and oriented along parallel paths. A small diameter (e.g., one- or two-inch) pipe much smaller than the conduit diameter serves as a stagnation waveguide to carry the signal between a corner reflector CR and one of the transducers so that the signal traveling between transducers A and B will be delayed differently in each direction when there is cross flow. This configuration allows cross flow to be sensed from a single side of the conduit. A similar corner reflector arrangement with a stagnation waveguide in one leg is shown in a pair of transducers C,D mounted on flanges oriented at 45° to the flow axis. In each case, both transducers of the pair might also be mounted on a single larger flange unit.

Other arrangements of transducers and different sensing systems are possible. Figure 14 shows an arrangement wherein three transducers A, B, C are located along a conduit, with transducers A and B located on the same side of the conduit to receive signals reflected specularly and coherently from the opposite wall, while transducer C is located across from A but well away from the center of its transmission lobe to receive transmitted energy predominantly from scatterers in the flowstream located in scattering cell Y2. Thus, the transmission and reflection paths are all on one pipe, but sufficiently different to allow electrically paralleling of the B and C transducer outputs into a single processing unit without external switching.

In Figure 14, a scattering cell Y1 is drawn near the midradius location, such that backscatter is received at transducer C' and forward scatter at transducer C", at arrival times approximately the same for C and C' but much earlier for transducer C". A transmission/ reception signal trace appears below the Figure. If C' and C" are the only receivers connected in parallel, the scatter shown in the time line as Y1, C' will be responsive primarily to axial flow, and relatively insensitive to cross-flow, whereas the scatter received by C" (the earlier arrival) is primarily responsive to cross-flow and relatively insensitive to axial flow. In other words, backscatter responds to axial flow and forward scatter to cross-flow, for the geometry illustrated. A scattering cell such as Y2 on or near the axis can be made appropriate for separating axial from cross-flow in the manner just described if one arranges that the arrival times for forward and backscatter are sufficiently well separated by more than the ringdown from anywhere in the scattering cell. One solution is to be sure that the two receivers that are in parallel are not symmetrically disposed about the scattering cell, that is, the two scatterer receivers are spaced different distances from the scattering cell, differing by more than the ringdown time t_{rd}, and furthermore, one is forward of the scattering cell, and the other behind it, forward and behind being reckoned with respect to the direction of axial flow, represented in Figure 14 by the arrow at the left side of the pipe.

More complex constructions are possible, or variations in which different pipes are interrogated but the transducers are wired together in parallel to utilize a common signal processor or flowmeter. Figure 15 shows one such system 540. This system includes three pipes 541, 542 and 543, each of which is illustrated with a different configuration of transducers interrogating it. Conduit 541 has a small diameter D1 and has a sending and a receiving transducer located diagonally opposite each other for direct transmission through fluid in the pipe. One transducer is connected to the transmission side of the flowmeter, the other to the receiving line. It will be understood that these lines are preferably switched within the meter itself to ultimately send and receive on each transducer for developing contrapropagation measurements. Conduit 542 is an identically sized pipe, however the transducers are arranged on the same side of the conduit to receive and send signals along a path approximately twice as long defined by reflection from the inside wall of the conduit.

Figure 15A shows an end view of pipe 541 representing crossed single- and double-traverse paths, with transducer A electrically wired in parallel with C and B in parallel with D. This is equivalent to the paralleling of transducers shown for pipe 541 and identical pipe 542, but now the crossed paths are utilized to detect asymmetry in the flow profile, so as to obtain a more accurate measure of flow. This is another instance of multipath interrogation in one pipe to improve accuracy or reduce uncertainty associated with the flow profile.

In Figure 15, another transducer is shown in phantom on the bottom of pipe 542, to indicate the classical configuration of opposed transducers with a three-leg reflected path between them. However a transducer is not used at this location, because a double-reflected, triple-traverse, path in the first pipe 541 would create substantial interference with such a signal which is displaced only slightly in the flow direction. Finally, the third conduit 543 is shown much larger than either of the other two. In this conduit, three pairs of transducers are illustrated which viewed from the leftmost to the rightmost pair illustrates different techniques for having the signal arrive in a spatially distinct time window so as to be processed on the same channel as the transducers from pipes 541 and 542. In the leftmost pair of sending and receiving transmitters, the transmitter is mounted with an appropriate wedge for directly transmitting from one transducer to the receiving transducer across the pipe of diameter 3D1. In the next one, the transducers are mounted via buffer rods to introduce a time lag between signal transmission and the signal entry into the conduit and fluid. This allows an even longer time separation for this second set of transducers. In the third (rightmost) pair of transducers, the transducers are mounted in a wedge angled to launch Rayleigh-like surface waves into the wall of the pipe which then radiates into the fluid and they are received along a path slightly offset from the end of the transducer mounting wedge.

This propagation through the wedge and conduit wall offers an additional range of delays for temporally separating the signals of the different transducers.

In all of the foregoing cases, the transmission occurs at the same instant in the transmitting transducer, while the delay interval to reception varies, allowing a single channel to process all received signals for the six different measurements. Each of these transit time variations is introduced in a clamp-on transducer assembly, allowing great flexibility in the overall configuration of systems. In general, the reception times may be adjusted by arranging differences in the diameter of the conduit, the angle of incidence, the type of wave traveling in the pipe wall (as has been extensively discussed above in connection with flexural wave transmission), the number of traverses, the difference in sound speed in the liquid, and the incident path length (e.g. short wedge or long buffer). In addition, the conduit may be deformed to change the path length in the liquid.

Pipes 541 and 542 may be taken to represent supply and return lines of equal cross-section of fuel, hydraulic fluid on an aircraft, or a cooling water supply and drain combination. In other words, the same liquid composition exists in both pipes. In this situation, the sound speed c in the liquid may be an accurate indicator of the instantaneous average temperature T in each of the interrogated segments, and hence of the density of the liquid in each pipe, and in particular, the difference in densities. By measuring both the flow velocity V and the sound speed c simultaneously in supply and return lines, one can obtain a fast-response measure of mass leakage. Note that in the absence of a density correction, a difference in V might merely be due to a temperature rise, and not at all due to a leak. Conversely, a temperature rise, if uncompensated, could mask a leak, as the V's might be the same in both conduits despite different mass flow rates.

If the fluid is compressible, such as a gas, determination of mass flowrate depends not only on V and T, but also on the pressure P. Gas pressure in principle is derivable from the amplitude of the gas borne signal, provided all attenuation effects and other non-pressure effects have been eliminated. Another method of obtaining fluid pressure, independent of pressure dependent transmission in the fluid, will be described below in connection with Figure 19.

Figure 17 shows a flow measurement system wherein a plurality of scatterers, Y1, Y2, Y3, Y4 are positioned at different stations across the diameter of a conduit along a path from a transmitting transducer T. Each reflector reflects signals to a receiving transducer R1', R2', R3', R4', all of which are connected in parallel to the processor section of a flowmeter. This provides a succession of increasingly long paths to the successive receivers so that each signal is received in a distinct time interval identified with one of the

scatterers Y_i. Taking the flow velocity V to be zero at the walls, a smooth flow profile is constructed and the pipe contents can be represented as the velocity at each station times the annular area of a ring about that station to provide a total mass flow rate for the conduit. In such a calculation, one would average the velocities obtained in scattering cells or stations symmetrically disposed about the axis. In very large pipes and/or in very attenuating fluids, it may not be practical to obtain scatter from stations beyond the centerline. In that case, one can obtain both forward and backscatter time-separated scatter signals, if one wants to quantify the axial and cross-flow components, as discussed previously.

Figure 16 shows a somewhat related embodiment wherein additional receiving transducers R5, R6, R7, R8 are located on the opposite side of the conduit. Each scatterer Y_i thus can provide a forward and a backscattered signal. However, note that the path T-Y1-R5 equals path T-Y2-R6, etc. Hence, paralleling R5-R8 tends to generate one composite scatter signal all in one window, as represented by the illustrated receive signal burst on the oscilloscope trace. This arrangement does not distinguish scatter from Y1, Y2, etc. To time-separate the signals, one cannot simply use any arrangement. One suitable time-separating arrangement is shown by the receivers R1-R4 at the top of this pipe, analogous to those on top of the pipe in Figure 17.

The idea of electrically paralleling isopaustic (same time delay) paths is not new. Examples of this idea appear in applicant's 1989 book, using pairs of parallel midradius chords. The problem with that isopaustically paralleled method, is that paths get weighted unintentionally in proportion to the electromechanical conversion efficiencies of the transducers used for each path. As all transducers cannot be manufactured identically, or one transducer may age or otherwise deteriorate differently from those used in other paths, the results in all paths will be affected when the signals are added or paralleled.

By time-separating the signals from each path in accordance with the present invention, the isopaustic problem is avoided.

There may, however, be compromise situations where it will be acceptable to parallel different pairs of isopaustic paths. For example, consider a Gauss-Chebyshev four-path spoolpiece which is to be manufactured subject to the constraints of minimizing the overall axial and radial lengths. This latter constraint could make it impractical to find four sufficiently different path lengths, but it may be possible to find only two different path lengths. Thus, one solution is to parallel electrically all four paths, but setting up the inboard pair and outboard pair to provide substantially isopaustic delays, differing from one another by the ringdown time. This preserves the fast-response characteristic of multiple paths in parallel, and still allows the electronics to distinguish inboard from outboard path signals.

Figure 18 shows another embodiment wherein flow is measured simultaneously along two separate conduits using a single channel flow meter. In this case, the interrogating transducers A, B for one conduit are spaced apart a different path length than the transducers C, D for the second conduit, and the transmission signals are initiated simultaneously so that transmitters and receivers both operate in parallel. In Figure 19, the transit time is adjusted by providing a different buffer path length from one transducer to a reflector located in the flow line. This approach allows a great range of adjustment so that separate conduits may readily be set up to operate in separate time intervals. Similarly, as shown in Figure 30, different conduits containing entirely distinct materials with different sound speeds may be interrogated in parallel with the slower sound speed delaying one signal to a separate time interval.

In Figure 20, the air path is long enough to allow enough time for the water transducer to ringdown and also to allow time for triple, quintuple,etc. reverberation paths in the water to die down.

Figure 19A shows an enlarged view of a transducer for use with fluids, liquids or gases but especially important when gas pressure P_g needs to be measured. It differs from the gas transducer of Figure 1B in several important respects. Within this transducer of Figure 19A, a solid path is included, having a transit time much less than the gas path transit time of path P_{19} in Figure 19. The solid path in Figure 19A includes a smooth unbonded dry interface 291 which may be self-aligning as illustrated by the wedge and channel shape shown in Figure 19B or, as illustrated in Figure 19A, mating parts may be mutually aligned by an acoustically-isolated or non-transmissive sleeve 292. Part of the acoustic energy generated in piezoelement 293 when energized via electrical connector 295a, travels to the right and is pressure-coupled across interface 291 by an amount that depends on, and which is approximately proportional to, the gas pressure P_g. The greater the pressure P_g, the greater is the pressure signal amplitude S_p appearing at electrical connector 295 connected electrically to the second piezoelement 294. One can arrange to put multiple interfaces like interface 291 in series, which increases sensitivity to P_g but at the undesirable expense of increasing complexity. Although the phenomenon of pressure coupling of ultrasonic waves is well known, examples being cited in applicant's 1989 book, applicant believes the use of pressure-coupling within a fluid-interrogating transducer assembly as illustrated in Figure 19A to measure gas pressure P_g is novel. Furthermore, applicant is not aware of any published account showing the importance of making the pressure-sensing path that includes one or more pressure-coupled interfaces very short compared to the fluid path interrogated by transducers electrically-paralleled with transducers 293 and 294.

While not strictly speaking a fluid, a flow of powdered material or such into a silo may be monitored by an overhead arrangement of transducers as shown in Figure 21, wherein a first pair of transducers are directed laterally at an overflow opening in the side of the silo, while a second pair are directed vertically to send and receive acoustic signals bounced off the top of the accumulated product in the silo. While the product may slump and pile irregularly and thus be a poor reflector, the minimal transit time does provide an indication of the maximum height achieved and the occlusion of an opening for the overflow path at the side of the silo provides an abrupt and distinct change in both path length and quality of the reflection seen by the second pair of transducers. Since the vertical path and oblique path are also of different lengths, these two pairs of sending and receiving transducers may be connected to a single transmitter/ receiver to operate as a height gage for the possibly non-reflective granular or powdered material in the silo. A reference reflector in the upper assembly placed close to the transducers may provide an initial return signal that serves as a timing reference, an overfill threshold for path length evaluation, or serves for setting an amplifier gain control.

Figure 22 shows yet another embodiment of a single channel device performing plural measurements in parallel. In this embodiment, a primary gas flow passes through a lower flow cell where transducers C and D interrogate the normal low flow path along an axial path through a small diameter conduit. Under conditions of greater flow, a flap or check-valve opens into a larger conduit where transducers A and B interrogate the flow across the conduit. Both sets of transducers are connected to a single instrument and the path lengths are arranged to provide reception signals in different windows when the transmission occurs simultaneously.

Figure 23 shows schematically a further arrangement wherein circulation or swirl measurements are taken along two separate conduits, or along two different size contours, or with two separate pairs of transducers taking clockwise and counterclockwise measurement in each conduit. Such arrangements may be useful in situations where the circulation must be measured at different places along the line of flow, or where substantially simultaneous clockwise and counterclockwise measurements at a single station along the pipe are required for each pipe. In this case, a two channel instrument is used, still showing a great economy over conventional circulation measurement systems.

Figure 24A shows a top and end view of transducer arrangements on a tapered trough or hopper in which measurements of liquid presence, liquid flow or other liquid characteristics are performed simultaneously at different stations along the height of the conduit.

Figure 24B shows similar top and end views for a rectangular channel. In this case, pairs of sending and receiving transducers are arranged at successively greater skew angles to obtain a sufficient path length differential for separation of the received signals.

This completes a description of the principles of the invention, together with illustrative embodiments and several preferred constructions for diverse transducer isolation and gas or other fluid sensing applications. The invention being thus disclosed, variations and modifications thereof will occur to those skilled in the art, and such variations and modifications are included within the scope of the invention to which an exclusive right is asserted, as defined by the claims appended hereto.

What is claimed is:

Claims:

1. A fluid measurement system comprising

a single channel measurement device having transmission means for producing a transmission signal to activate an acoustic transducer to propagate signal energy and also having a single channel signal reception means for processing electrical signals from a transducer that receives the signal energy,

means defining a fluid region containing a fluid to be measured by propagation of said signal energy, and

means mounting a plurality of transducers for acoustic interrogation of fluid energy in said region, said means mounting at least two of said plurality of transducers as receiving transducers in receiving paths such that they receive such signal energy at separate and non-interfering time intervals when said measurement device produces a single transmission signal, so that the single channel reception means processes the signal energy received by said receiving transducers means to perform fluid measurement.

2. A fluid measurement system according to claim 1, wherein said mounting means includes clamp-on-transducer mountings which position receiving transducers at different path lengths from one or more acoustic transducers simultaneously driven by said actuation signal.

3. A fluid measurement system according to claim 1, wherein the transducers in receiving paths include transducers located on a plurality of separate conduits.

4. A measurement system according to claim 1, wherein the transducers in receiving paths perform at least two different measurements selected from among axial flow, cross-flow, pressure, temperature, liquid level and circulation measurements.

5. A measurement system according to claim 1, wherein the transducers in receiving paths include at least first and second transducers that receive acoustic energy that is primarily reflected off fixed targets and primarily scattered from scatterers moving with the fluid, respectively.

6. A fluid measurement system according to claim 1, wherein signal transit times along said paths are approximately proportional to a sequence of prime numbers, which may be consecutive prime numbers.

7. A fluid measurement system according to claim 1, which is a gas measurement system interrogated by acoustic waves of period P, and wherein said receiving paths determine adjacent time intervals that are separated by an interval of at least 50P.

8. A fluid measurement system according to claim 1, wherein the receiving transducers sense at least two distinct measurements from the same transmission, the measurements being selected from among axial flow, cross-flow and swirl.

9. A fluid measurement system according to claim 1, comprising a scattering cell, and wherein receiving transducers are located forward and back of each other in relation to the scattering cell such that they receive acoustic energy from a single transmitting transducer along different paths as acoustic energy is scattered by the scattering cell, for determining both axial flow and cross-flow.

10. A fluid measurement system according to claim 1, wherein one of said transducers includes a transducer assembly having a housing, a transmitting transducer mounted in the housing for transmitting a signal through the fluid, a reference receiving transducer in the housing, and material coupling the transmitting and reference receiving transducers to each other, the material varying its transmission characteristics in accordance with fluid pressure applied thereto, said material providing a short acoustic path such that the reference receiving transducer receives a signal representative of fluid pressure in an initial time interval before receiving a signal transmitted through the fluid.

11. A fluid measurement system according to claim 1, wherein the mounting means includes at least two axially-separated strap-mounted transducer assemblies.

12. A fluid measurement system according to claim 1, wherein said mounting means includes an open frame that holds transducers directed along acoustic paths in at least two different planes for measuring characteristics of an unconstrained fluid.

13. A fluid measurement system according to claim 1, wherein the mounting means clamps on to orient a first transducer to direct acoustic energy in a plane, and a second transducer to direct acoustic energy transverse to said plane.

14. A fluid measurement system according to claim 1, wherein the single channel measurement device processes and completes processing of said signals within a time interval substantially equal to transit time of said acoustic interrogation.

15. An isolation mounting for isolating an ultrasonic transducer element from surrounding elements of an ultrasonic measurement system to remove solid body noise transmission along a measurement axis, such isolation mounting comprising a flange and at least one O-ring bearing against the flange in the direction of said axis to interrupt acoustic contact.

16. An isolation mounting according to claim 15, comprising a pair of O-rings forming a sandwich with said flange.

17. An isolation mounting according to claim 15, wherein said flange is a conduit flange.

18. An isolation mounting according to claim 17, wherein the O-ring seats against an axially-directed face of the conduit.

19. An isolation mounting according to claim 17, wherein the O-ring seats in a chordally-directed bore in said flange.

20. An isolation mounting according to claim 15, wherein said flange is a flange of a cylindrical casing that houses said ultrasonic transducer element.

21. An isolation mounting according to claim 15, wherein said O-ring forms a primary seal for containing fluid in a container and said O-ring is compressed under 40% of its thickness.

22. An isolation mounting according to claim 15, wherein said O-ring forms a secondary seal for containing fluid in a container.

23. An isolation structure for interposing in a solid acoustic path between ultrasonic elements transmitting and receiving signals through a gas to attenuate noise transmitted along said solid path, and comprising a plurality of high impedance and low impedance segments arranged in series along the path, said segments being formed of elastic material and said low impedance segments having a thickness $<< \lambda/10$, where λ is the wavelength of said signals in the solid acoustic path.

24. A measurement system comprising
housing means defining a flow channel
a plurality of closely spaced ultrasonic transducer elements each mounted in the housing means and directed along a measurement path and having mounting means for isolating at least one transducer element from the housing means.

25. A measurement system according to claim 24, wherein the system comprises two transducer elements which transmit and receive signals along three chordal segments to measure circulation about a flow axis.

26. A measurement system according to claim 24, wherein the system comprises at least two transducer elements that transmit and receive signals along a set of at least three segments, the set of segments together forming a closed contour lying substantially in a plane.

27. A measurement system according to claim 26, wherein the flow channel has an enlarged region with a substantially circular cross-section, and said closed contour is comprised of mid-radius chordal segments of said cross-section to measure circulation.

28. A measurement cell assembly comprising
a flow cell having a conduit for containing a fluid along a measurement path, the conduit having a thin wall to provide low phase velocity of acoustic signals propagated therethrough, and
a frame for rigidly fixing measurement ends of the conduit, said frame including isolation means for acoustically decoupling the frame between said ends.

29. A measurement system for measurement of ultrasonic wave energy in a gas, such system comprising
a thin-walled conduit
a pair of transducer elements for transmitting and receiving ultrasonic wave energy along a path of length L in the conduit
means for scattering energy in said thin-walled conduit of ultrasonic waves in said gas reflected from the conduit and
a plurality of masses spaced apart from each other and each contacting the conduit wall along the path.

30. A measurement system, comprising

wall means defining a fluid flow chamber

a first plurality of ultrasonic transducer elements being acoustically isolated from said wall means and defining a first at least approximately planar closed signal path lying at least approximately in a first plane

a second plurality of ultrasonic transducer elements being acoustically isolated from said wall means and defining a second at least approximately planar closed signal path lying at least approximately in a second plane.

31. A measurement system according to claim 30, wherein said second plane is either orthogonal to said first plane, or is adjacent to and parallel to said first plane.

32. A measurement system according to claim 31, further comprising reflectors that define at least part of at least one of said first and second signal paths.

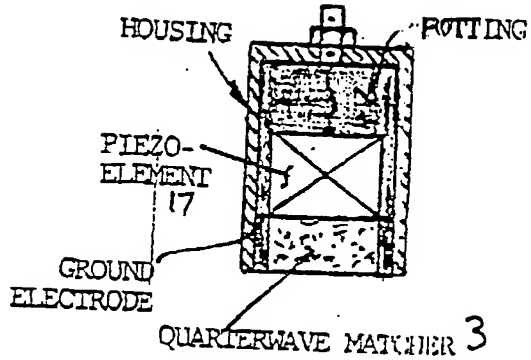


FIGURE 1B

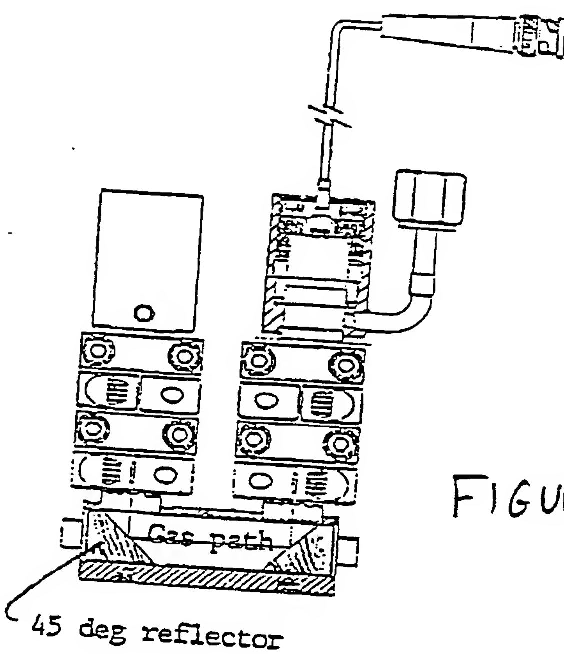


FIGURE 1A

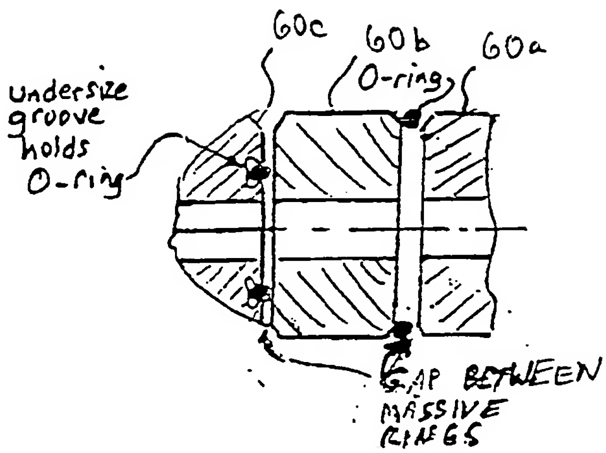


FIG. 2A

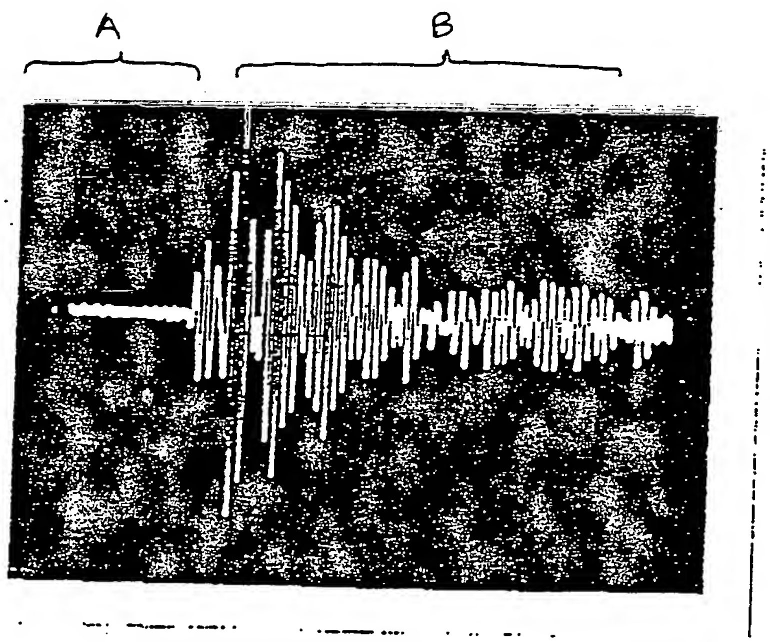


FIG. 2B. Oscillogram of the received waveform, obtained with the cell of Figure 1A (U-shaped cell).

It is seen that there is relatively little crosstalk in the "A" portion of the trace, compared to the signal strength in the "B: portion of the trace. In this test the gas was air at ordinary conditions of temperature and pressure.

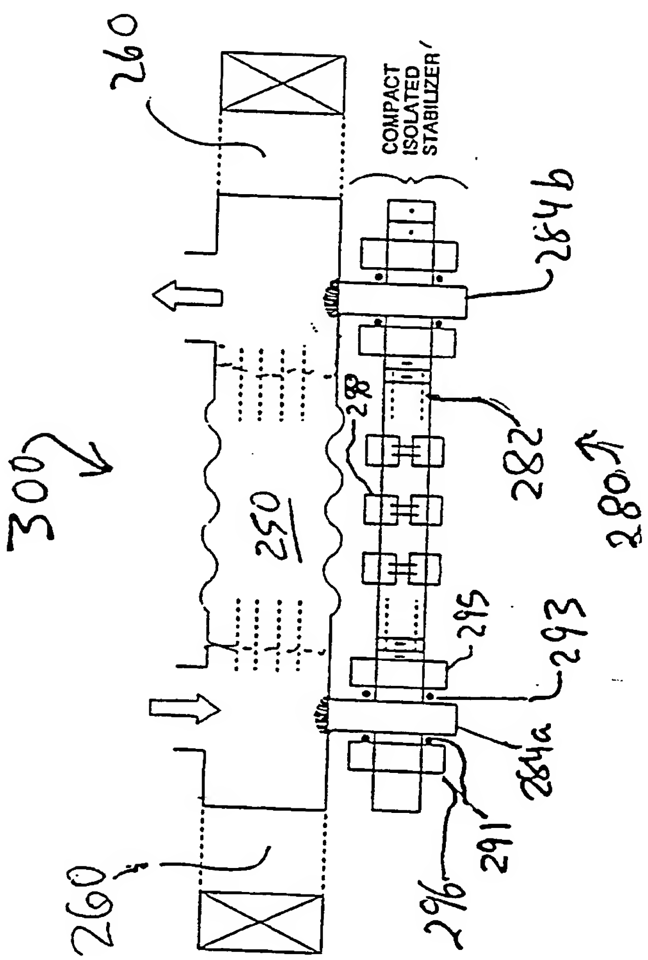

300
260
250
COMPACT
ISOLATED
STABILIZER
284b
298
282
280
295
293
284a
291
296
260

FIGURE 3

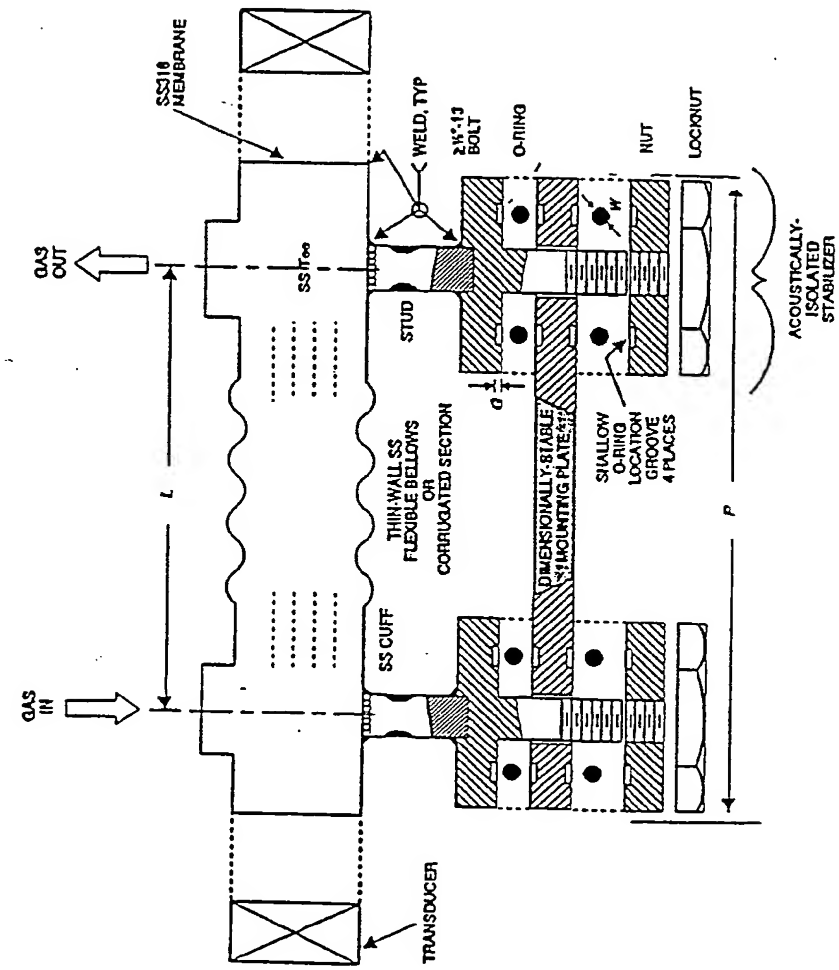

GAS OUT
GAS IN
SS316 MEMBRANE
WELD, TYP
BOLT
O-RING
NUT
LOCKNUT
SS Tee
STUD
THIN-WALL SS FLEXIBLE BELLOWS OR CORRUGATED SECTION
SS CUFF
SHALLOW O-RING LOCATION GROOVE 4 PLACES
ACOUSTICALLY-ISOLATED STABILIZER
TRANSDUCER
L
P

FIGURE 4

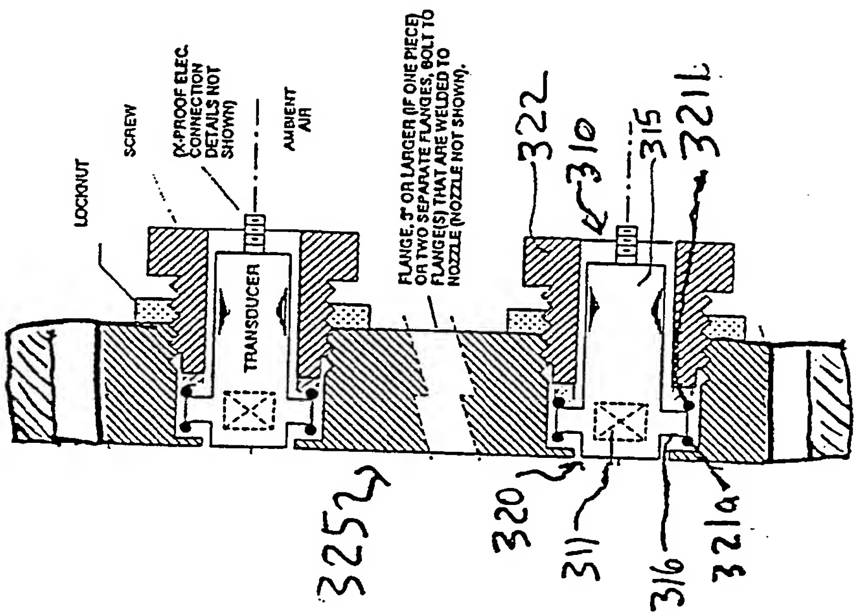

LOCKNUT
SCREW
(X-PROOF ELEC. CONNECTION DETAILS NOT SHOWN)
AMBIENT AIR
TRANSDUCER
FLANGE, 3" OR LARGER (IF ONE PIECE) OR TWO SEPARATE FLANGES, BOLT TO FLANGE(S) THAT ARE WELDED TO NOZZLE (NOZZLE NOT SHOWN).
322
310
315
321L
325
320
311
316
321a

FIGURE 5

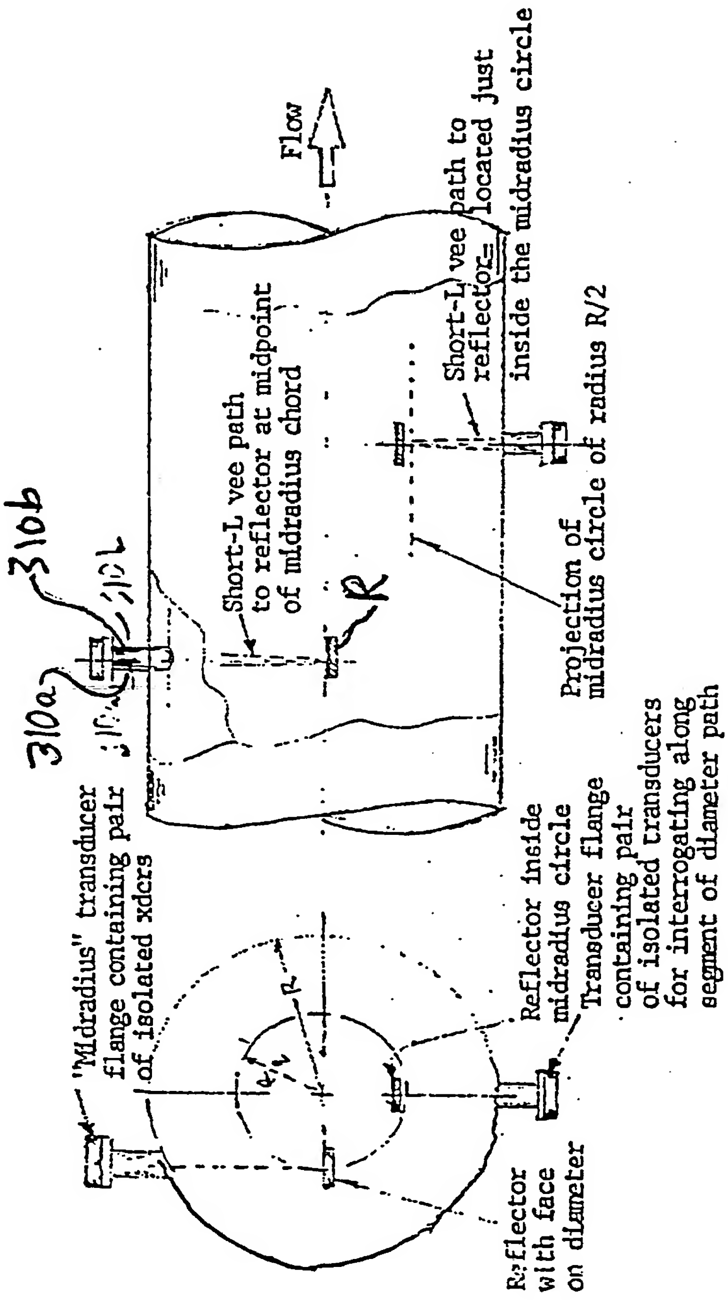

"Midradius" transducer flange containing pair of isolated xdcrs
Reflector with face on diameter
R
Reflector inside midradius circle
Transducer flange containing pair of isolated transducers for interrogating along segment of diameter path
310a
310b
R
Short-L vee path to reflector at midpoint of midradius chord
Projection of midradius circle of radius R/2
Short-L vee path to reflector located just inside the midradius circle
Flow

FIGURE 5A

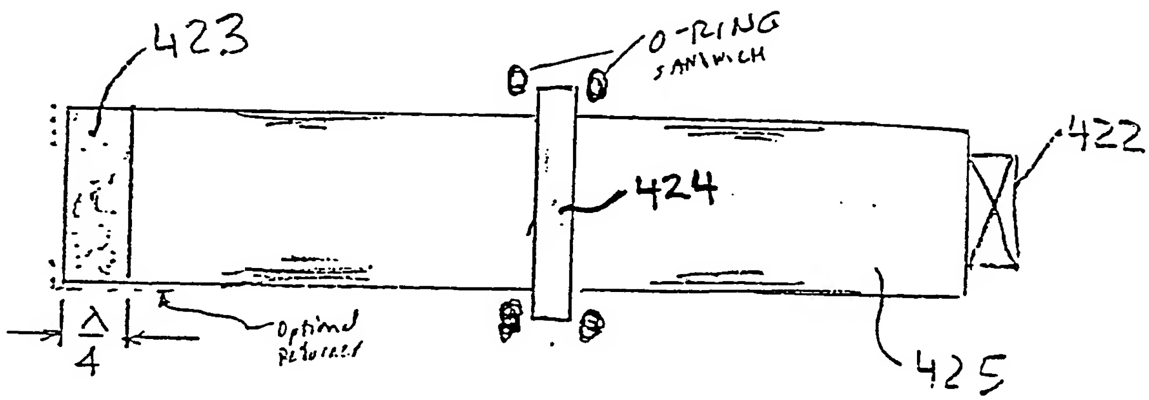


FIGURE 5C

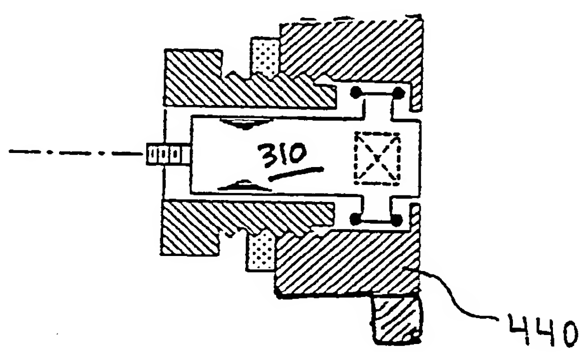


FIGURE 5D

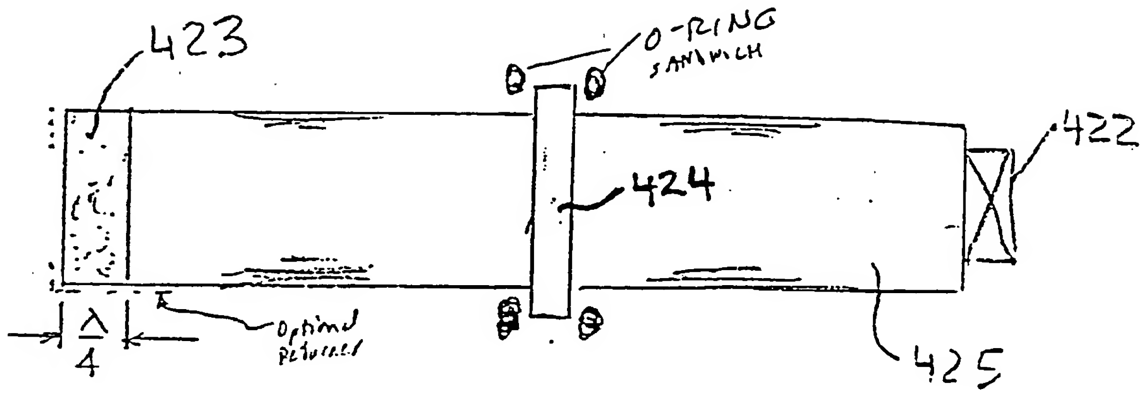


FIGURE 5C

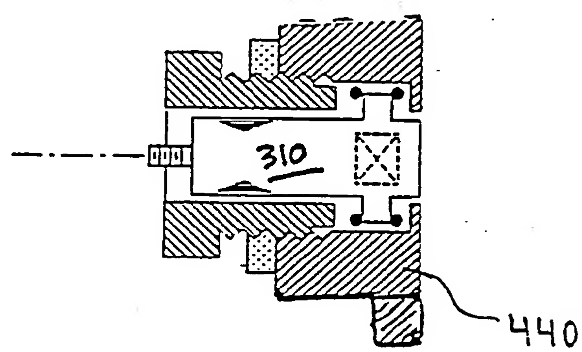


FIGURE 5D

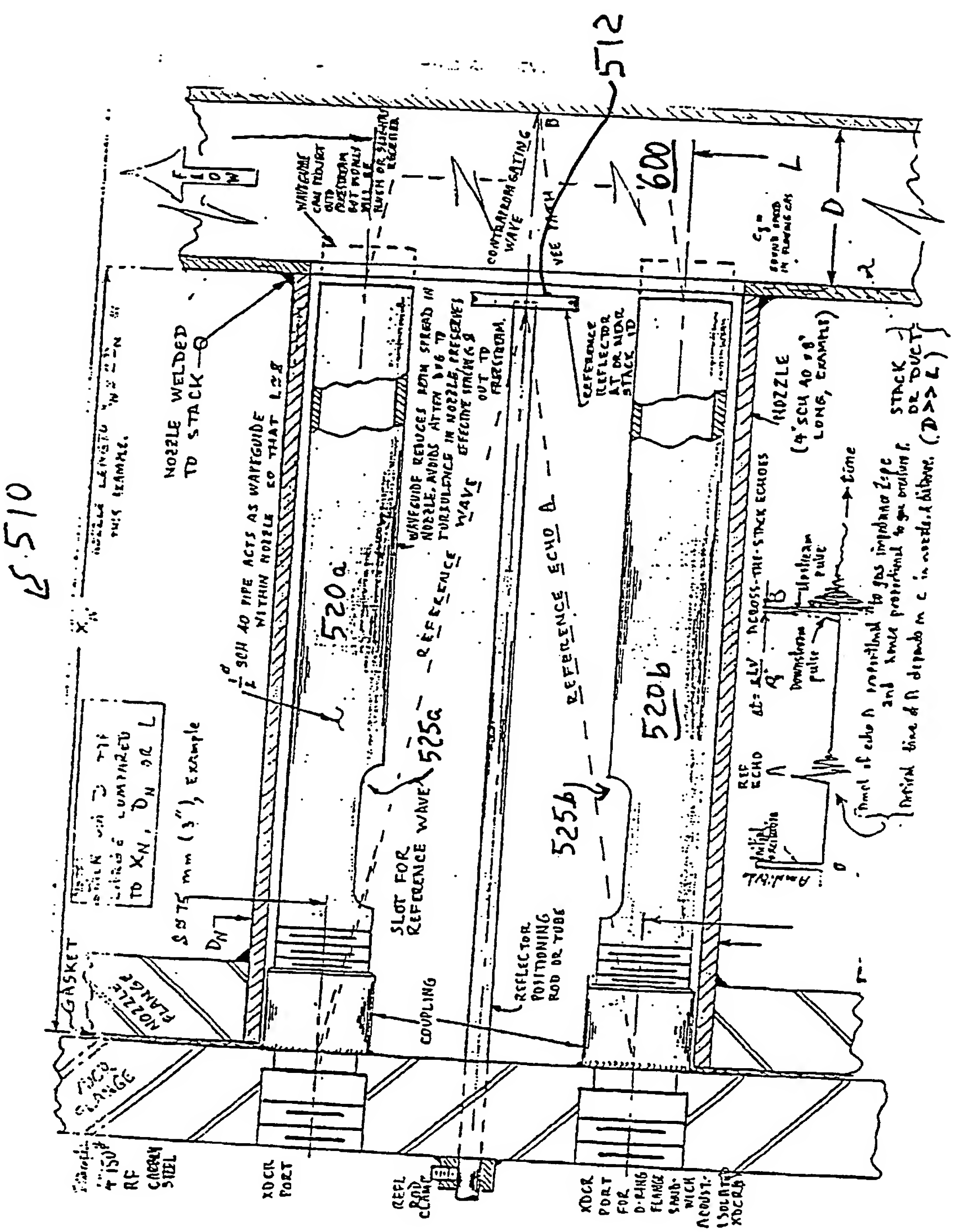

510
512
600
NOZZLE WELDED TO STACK
520a
520b
525a
525b
SLOT FOR REFERENCE WAVE
REFERENCE ECHO A
REFERENCE WAVE
COUPLING
REFLECTOR POSITIONING ROD OR TUBE
GASKET
NOZZLE FLANGE
XDCR PORT
NOZZLE
STACK OR DUCT
FLOW
D
L

FIGURE 5E

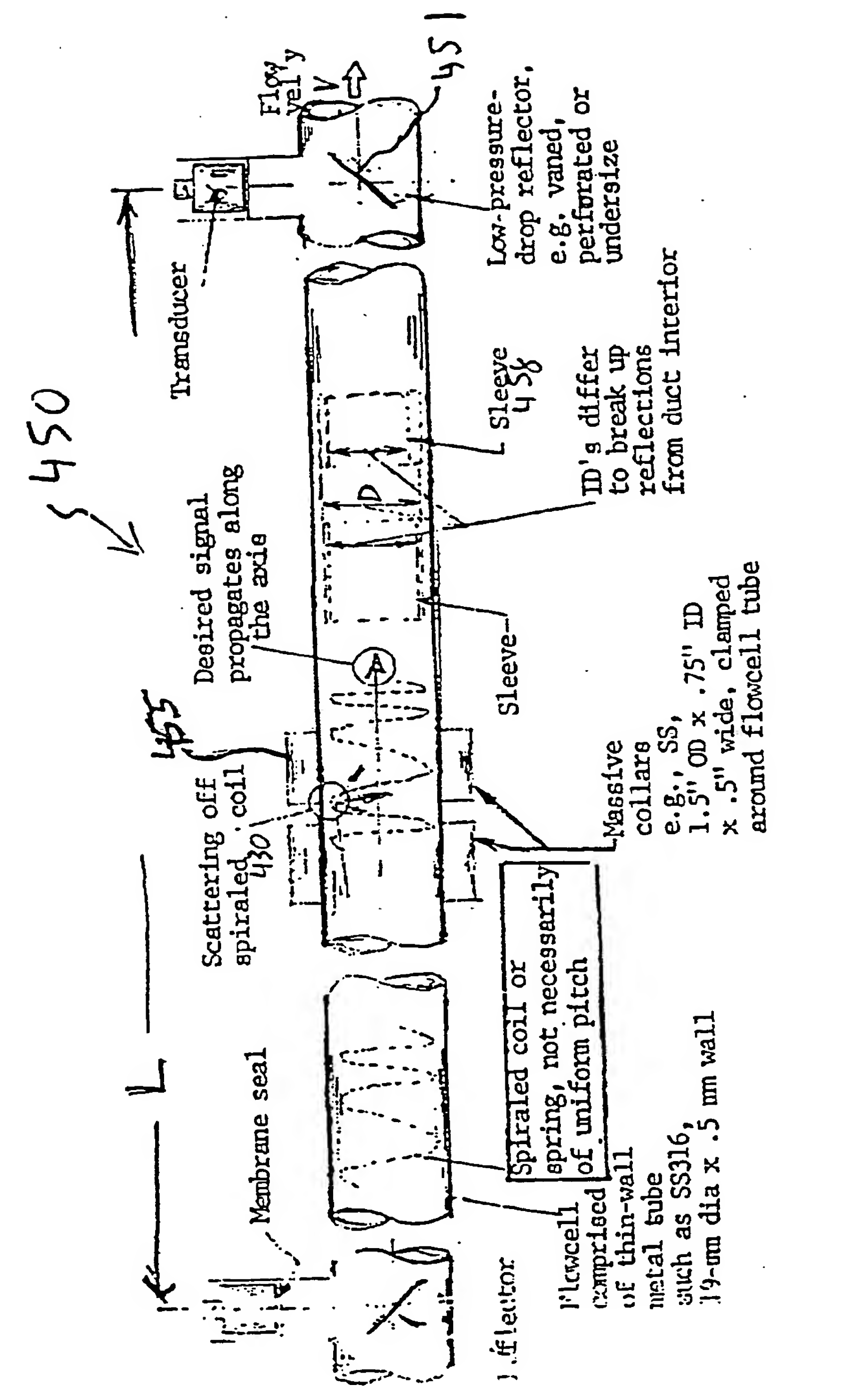

450
451
Flow vel'y
V
Transducer
Low-pressure-drop reflector, e.g. vaned, perforated or undersize
Sleeve 458
ID's differ to break up reflections from duct interior
Desired signal propagates along the axis
A
Sleeve
455
Scattering off spiraled coil 430
Massive collars e.g., SS, 1.5" OD x .75" ID x .5" wide, clamped around flowcell tube
Spiraled coil or spring, not necessarily of uniform pitch
L
Membrane seal
Flowcell comprised of thin-wall metal tube such as SS316, 19-mm dia x .5 mm wall
Reflector

FIGURE 6

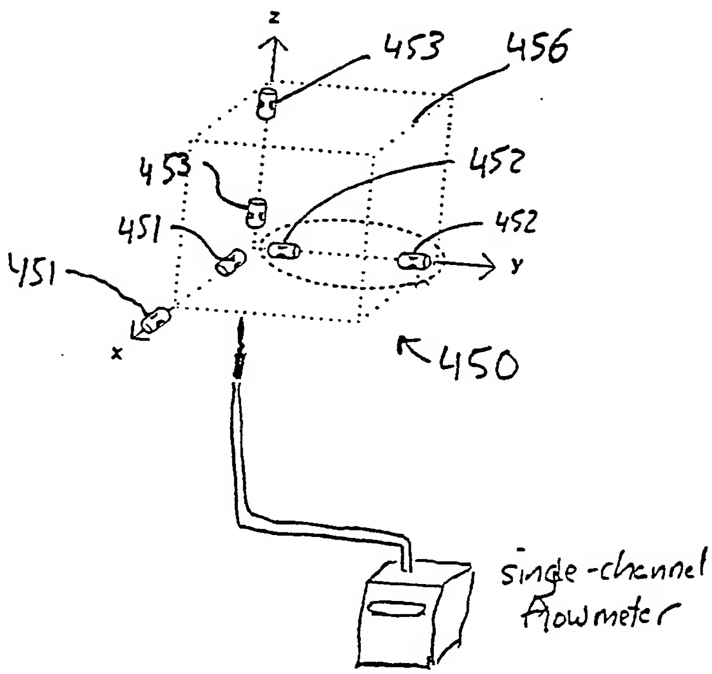


FIGURE 7

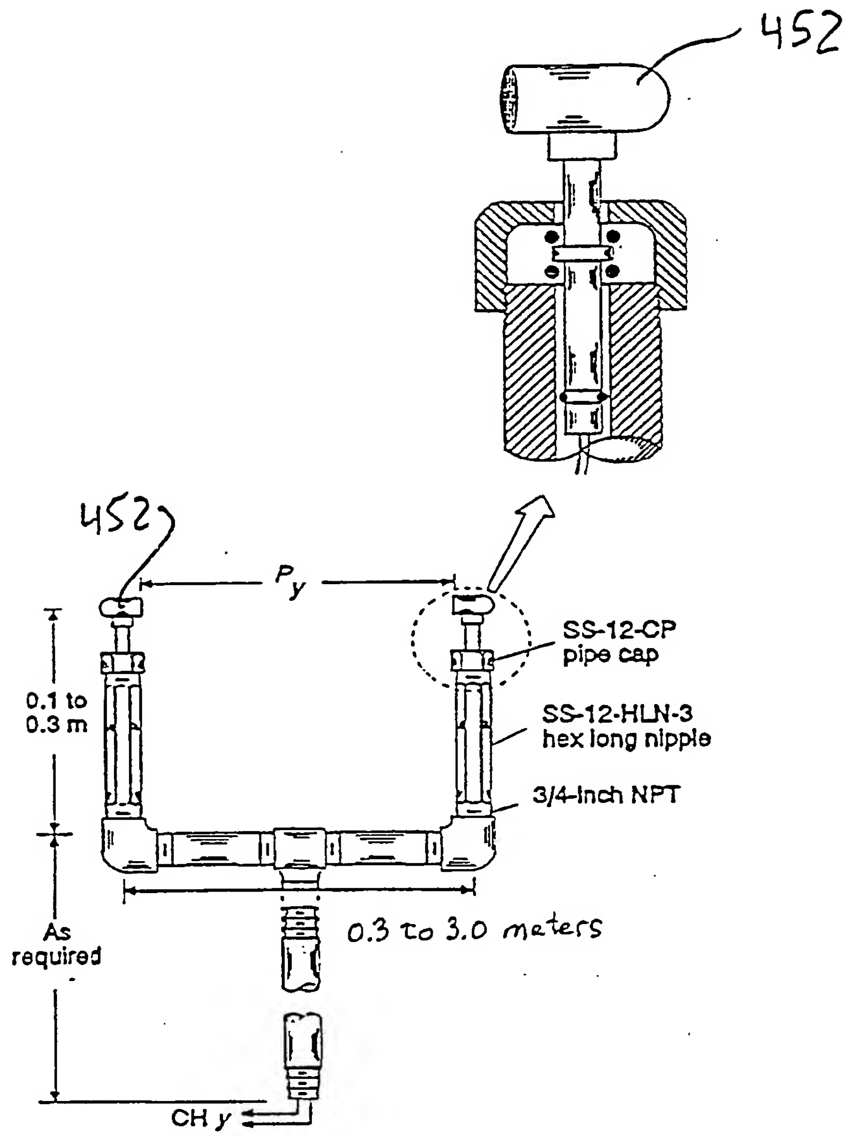

452
452
P_y
0.1 to
0.3 m
SS-12-CP
pipe cap
SS-12-HLN-3
hex long nipple
3/4-inch NPT
As
required
0.3 to 3.0 meters
CH y

FIGURE 7A

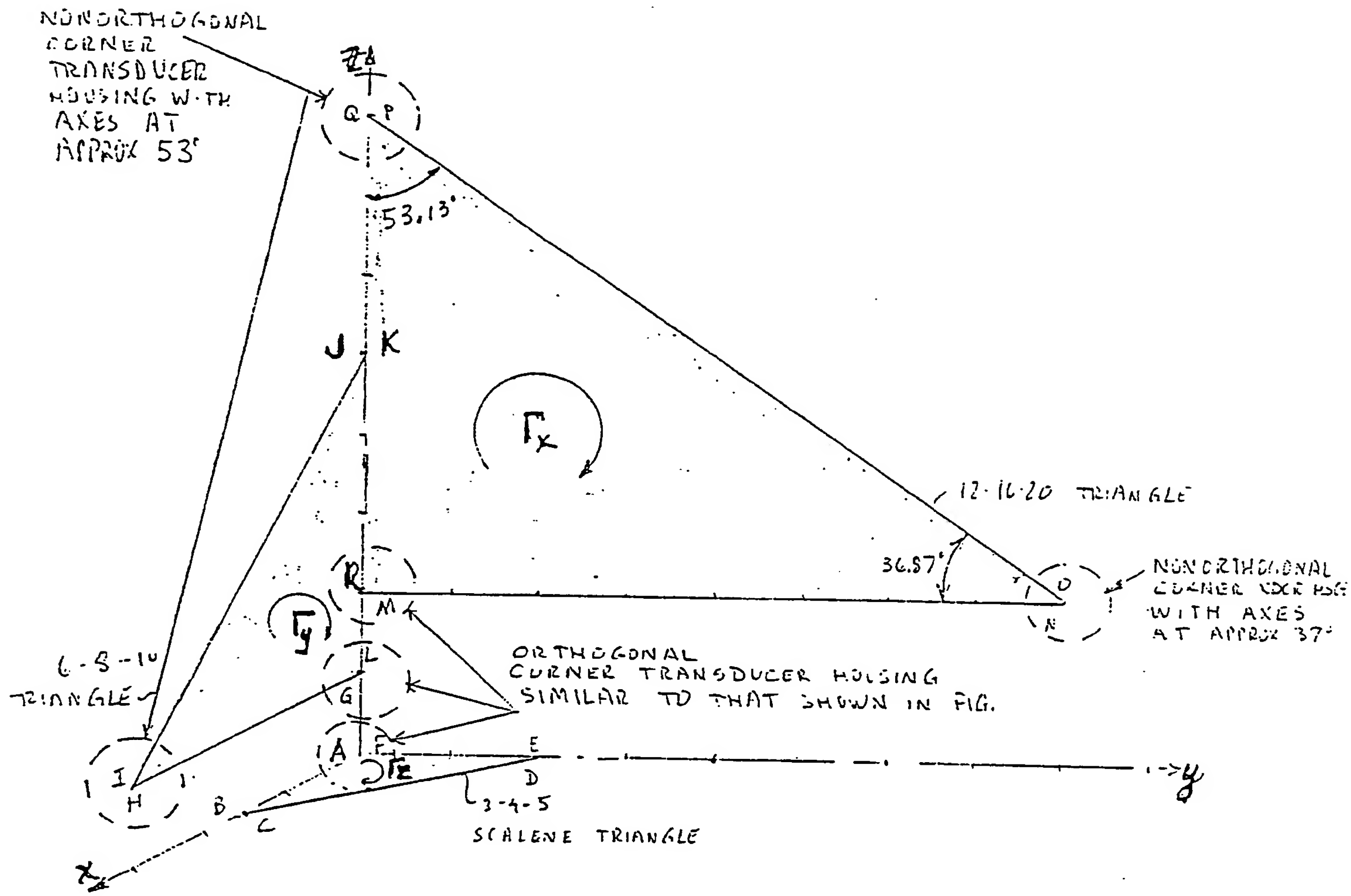
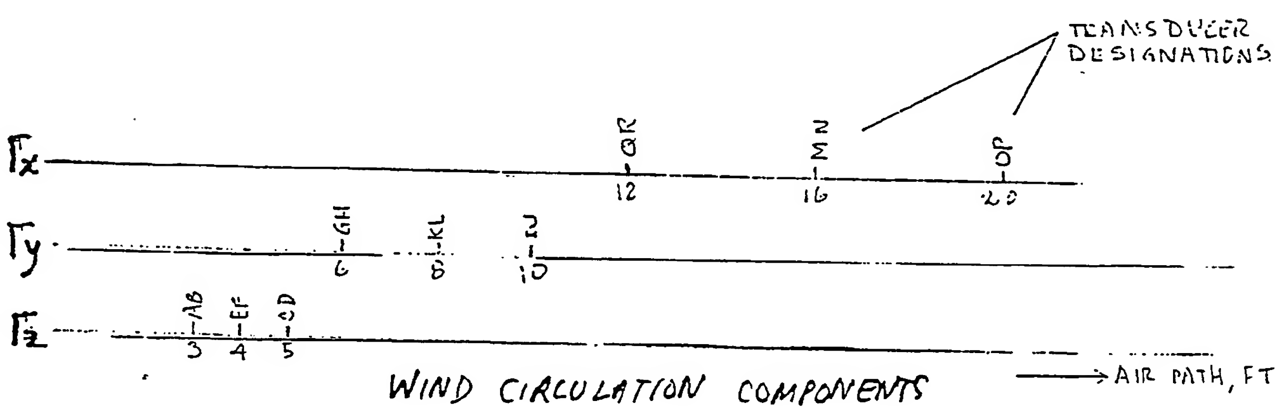


FIGURE 7B



WIND CIRCULATION COMPONENTS

FIGURE 7D

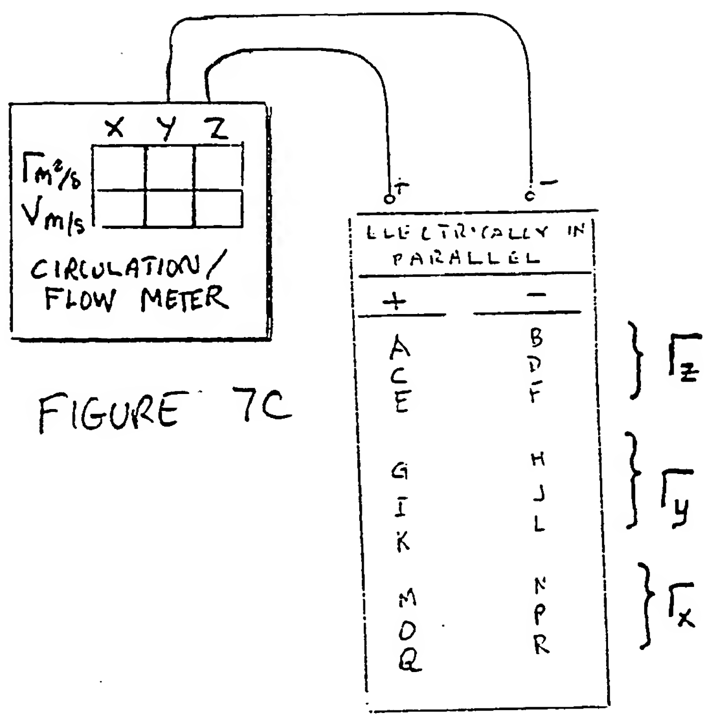

X Y Z
Γm²/s
Vm/s
CIRCULATION/
FLOW METER
+
−
ELECTRICALLY IN
PARALLEL
+
−
A
C
E
B
D
F
Γz
G
I
K
H
J
L
Γy
M
O
Q
N
P
R
Γx

FIGURE 7C

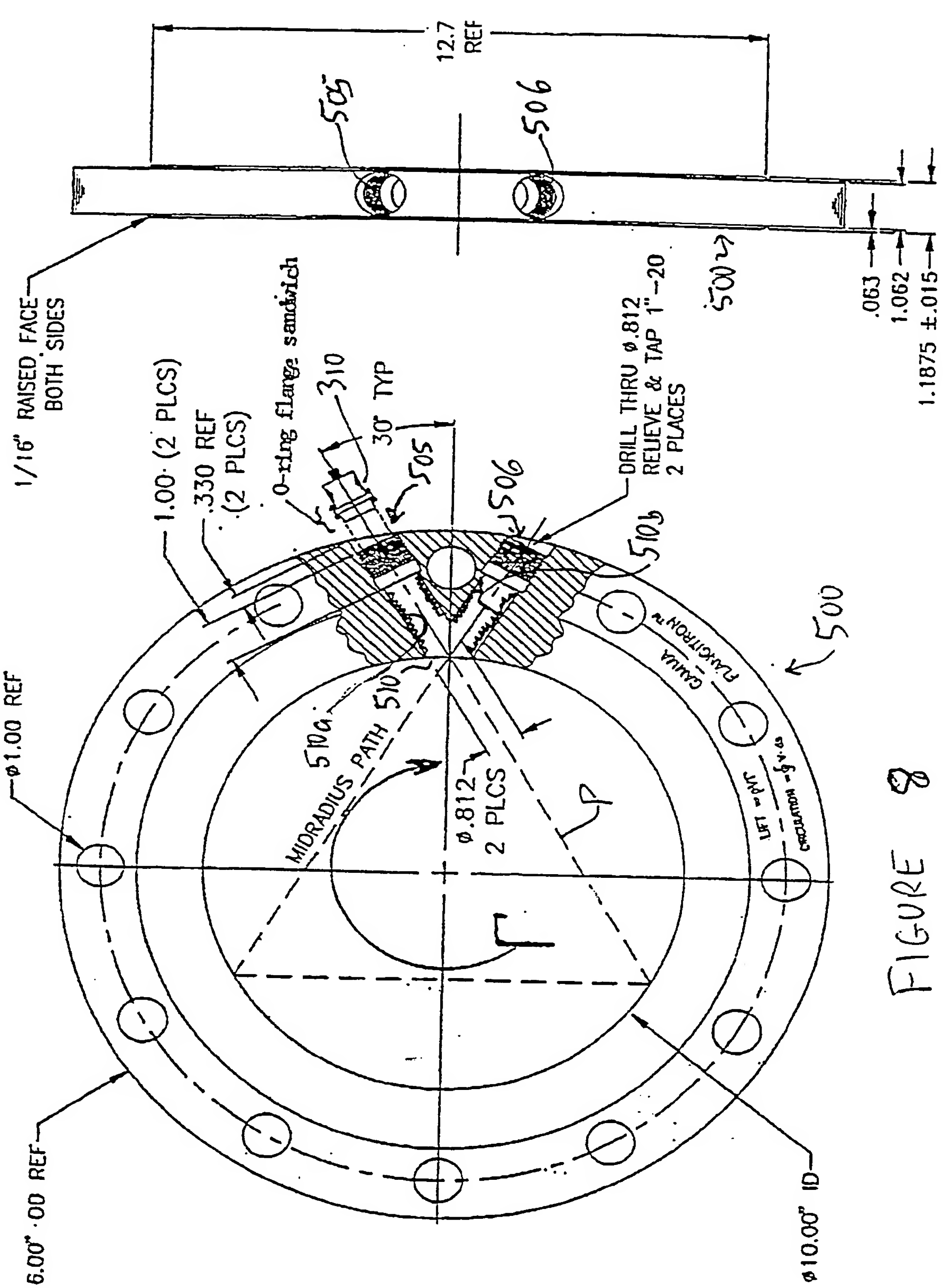


FIGURE 8A

FIGURE 8

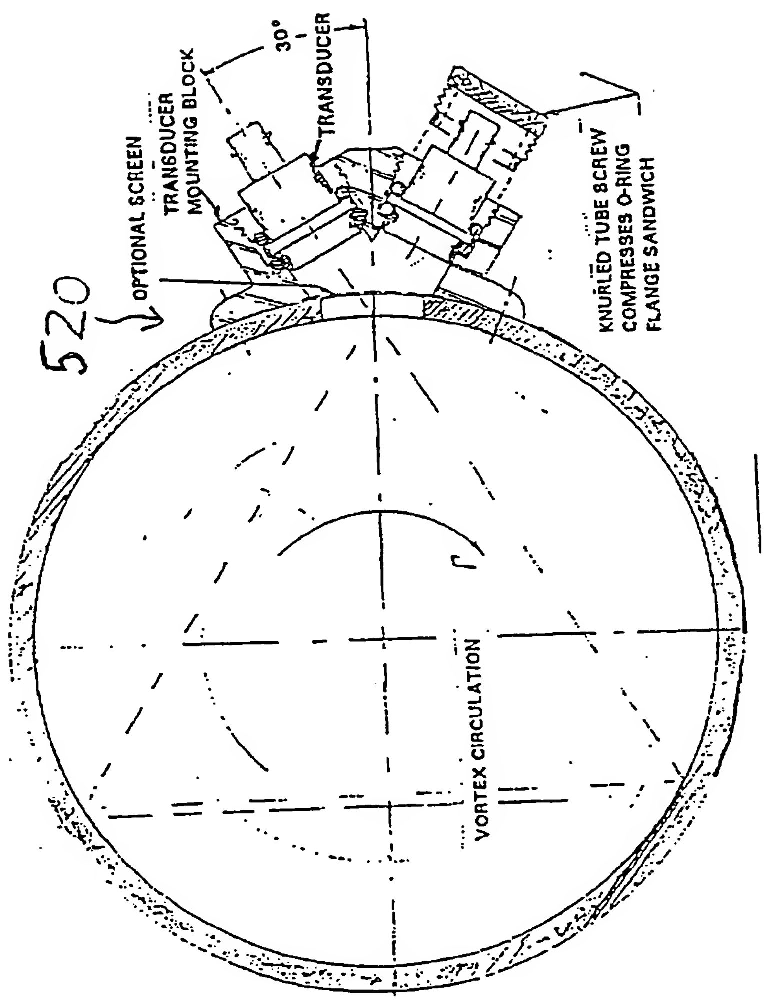

520
OPTIONAL SCREEN
TRANSDUCER MOUNTING BLOCK
TRANSDUCER
30°
KNURLED TUBE SCREW COMPRESSES O-RING FLANGE SANDWICH
VORTEX CIRCULATION

FIGURE 9

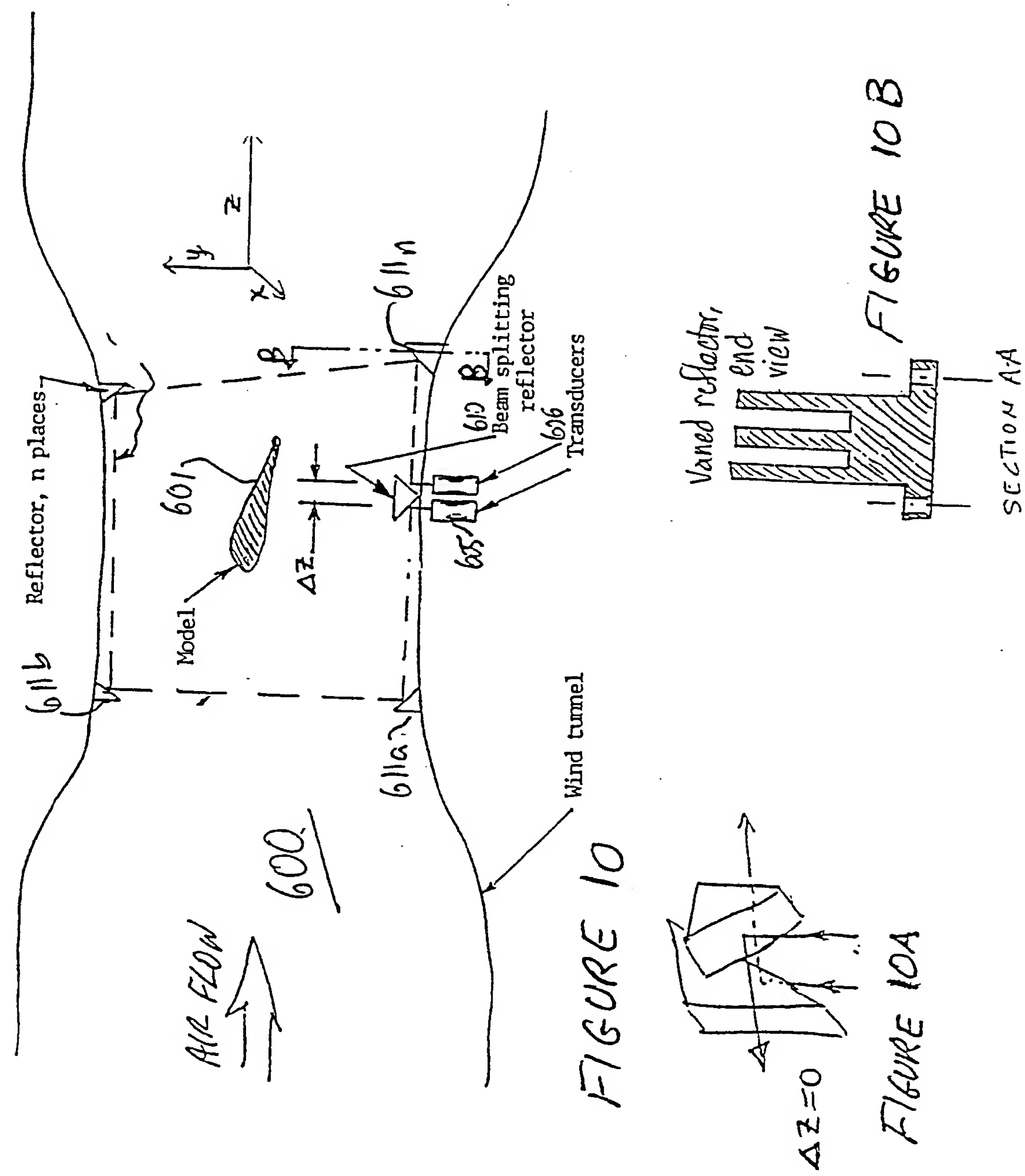


FIGURE 10

FIGURE 10A

FIGURE 10B

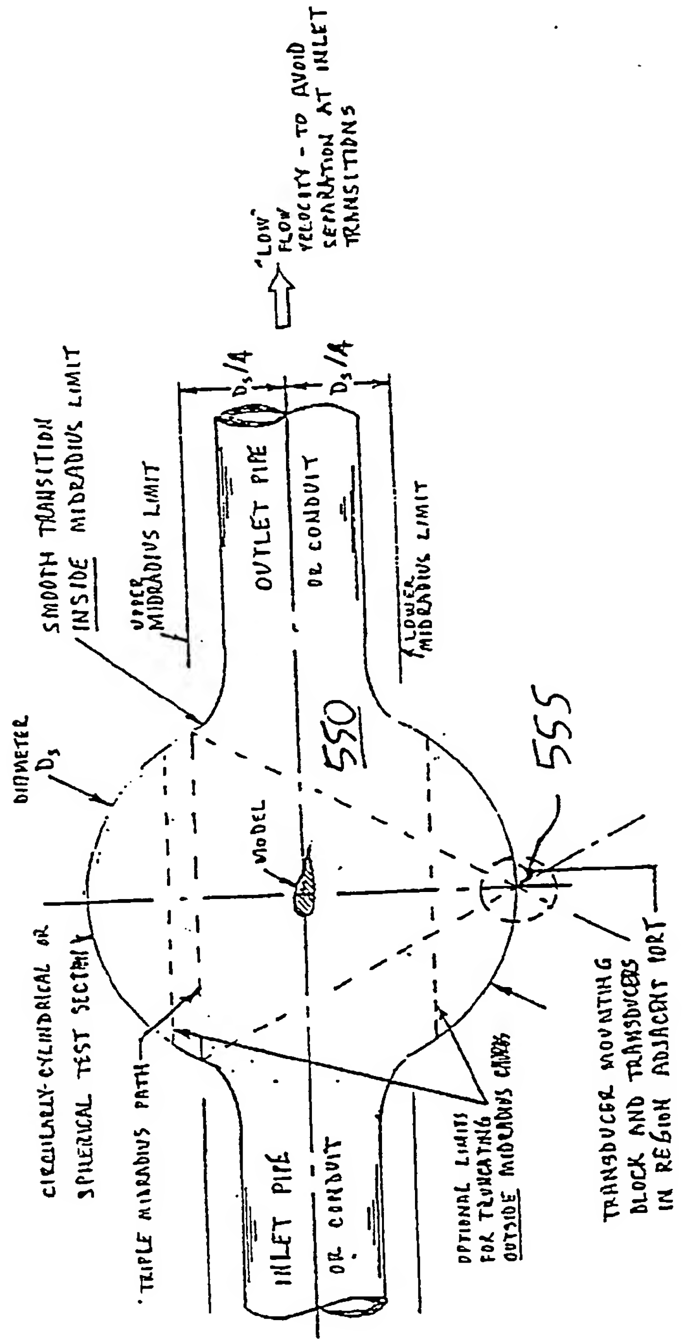


FIGURE 11

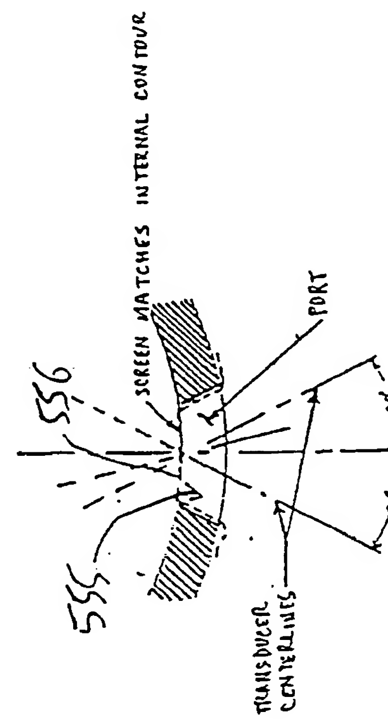


FIGURE 11A

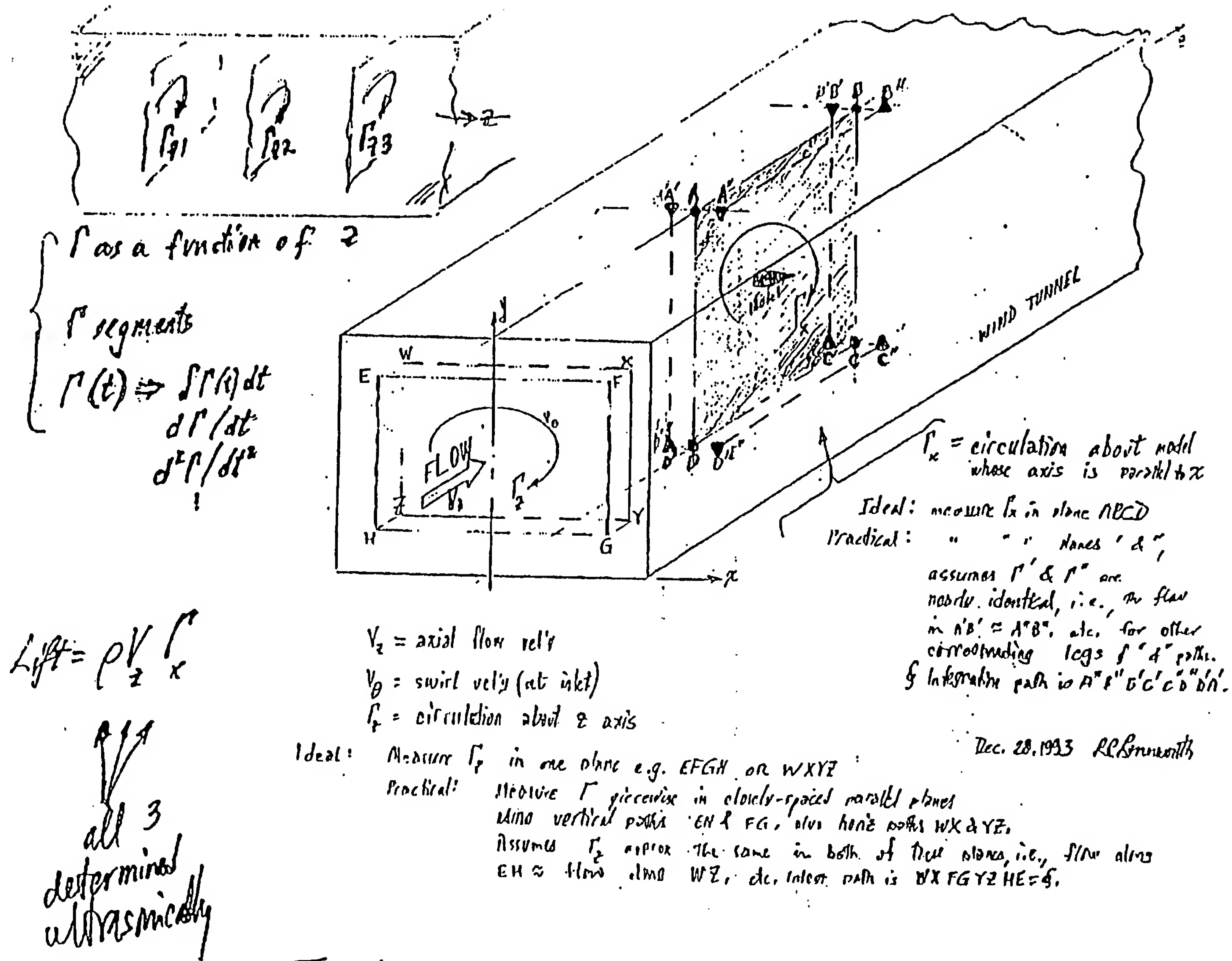

WIND TUNNEL
FLOW
Γ as a function of z
Γ segments
Γ(t) ⇒ ∫Γ(t)dt
dΓ/dt
d²Γ/dt²
Lift = ρ V_z Γ_x
all 3 determined ultrasonically
V_z = axial flow vel'y
V_θ = swirl vel'y (at inlet)
Γ_z = circulation about z axis
Ideal: Measure Γ_z in one plane e.g. EFGH or WXYZ
Practical: Measure Γ piecewise in closely-spaced parallel planes using vertical paths EH & FG, plus horiz paths WX & YZ.
Assume Γ_z approx the same in both of these planes, i.e., flow along EH ≈ flow along WZ, etc. Integr. path is WXFGYZHE=Γ.
Γ_x = circulation about model whose axis is parallel to x
Ideal: measure Γ_x in plane ABCD
Practical: " " " planes ' & ",
assumes Γ' & Γ" are nearly identical, i.e., the flow in A'B' = A"B", etc. for other corresponding legs of ' & " paths.
& Integration path is A"B"B'C'C"D"D'A'.
Dec. 28, 1993 RCBrunworth

FIGURE 12

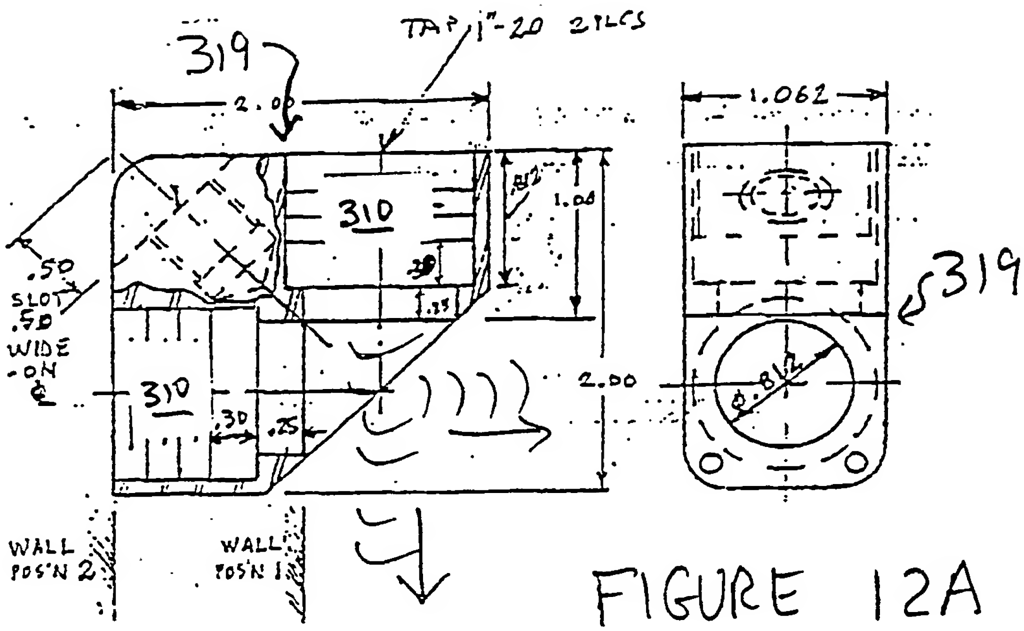


FIGURE 12A

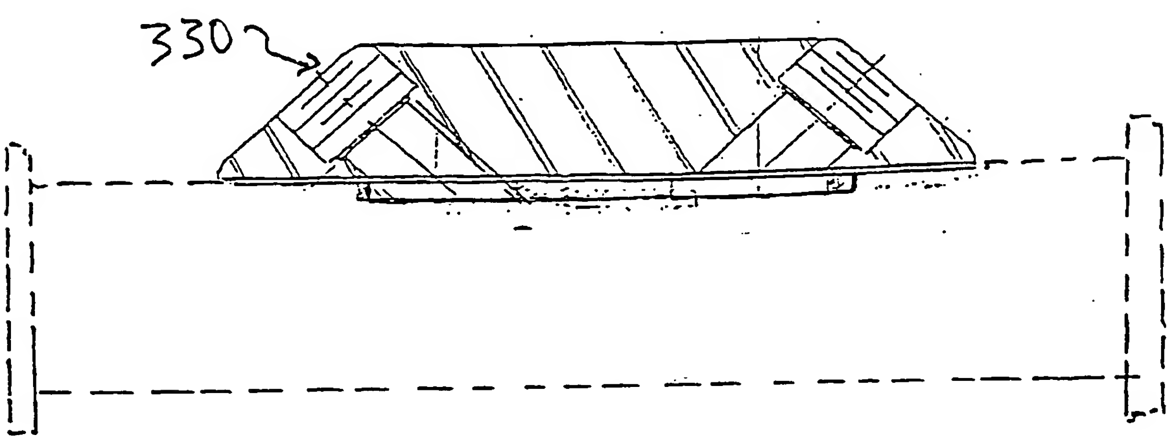


FIGURE 12B

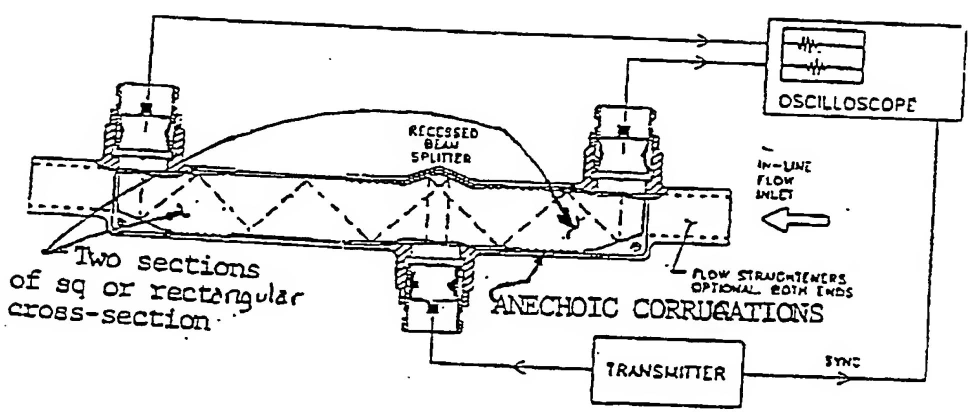

OSCILLOSCOPE
RECESSED BEAM SPLITTER
IN-LINE FLOW INLET
Two sections of sq or rectangular cross-section
FLOW STRAIGHTENERS OPTIONAL BOTH ENDS
ANECHOIC CORRUGATIONS
TRANSMITTER
SYNC

FIGURE 12C

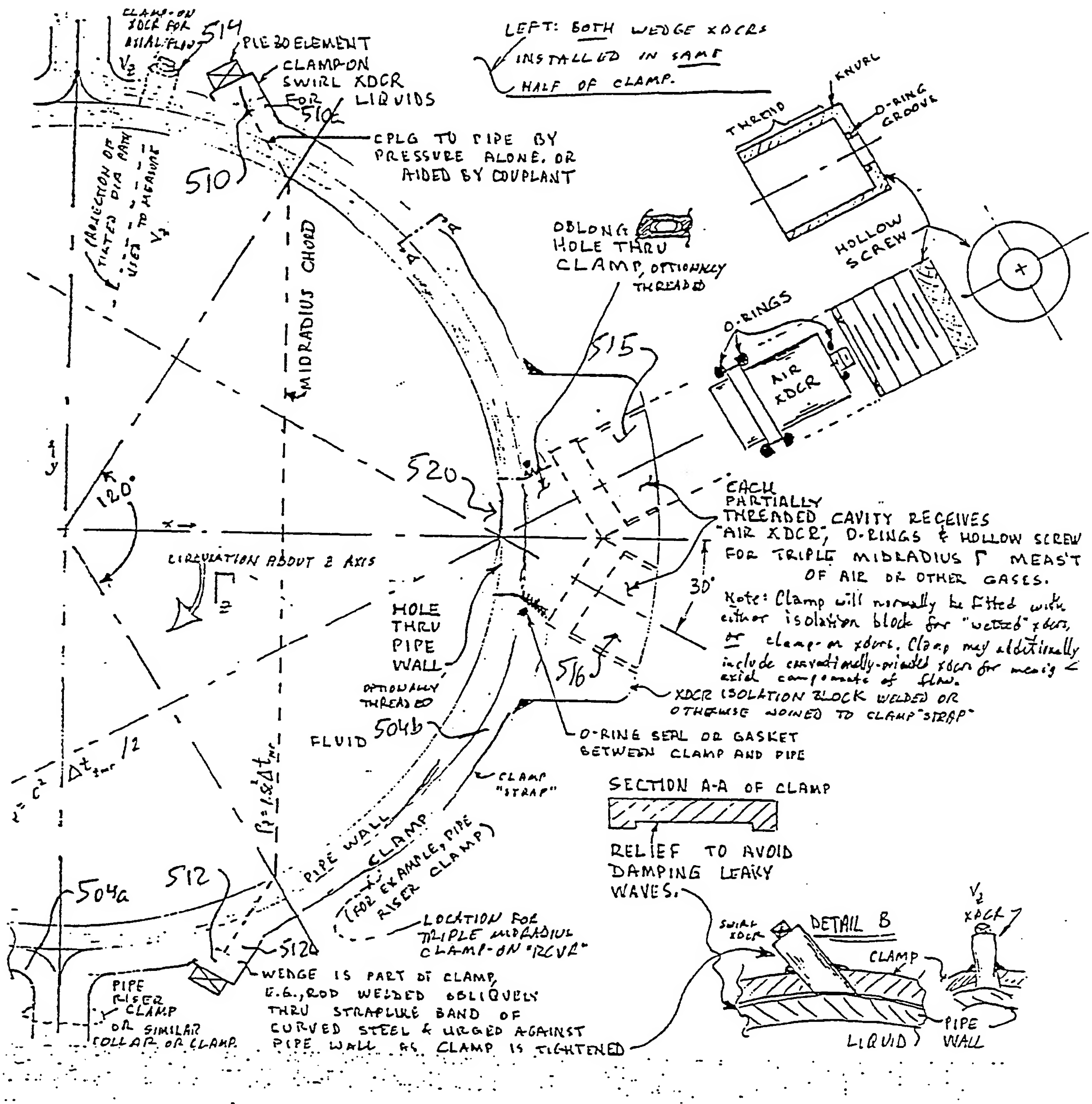

CLAMP-ON XDCR FOR AXIAL FLOW
514
PIEZO ELEMENT
CLAMP-ON SWIRL XDCR FOR LIQUIDS
510c
CPLG TO PIPE BY PRESSURE ALONE, OR AIDED BY COUPLANT
510
LEFT: BOTH WEDGE XDCRS INSTALLED IN SAME HALF OF CLAMP.
THREAD
KNURL
O-RING GROOVE
HOLLOW SCREW
OBLONG HOLE THRU CLAMP, OPTIONALLY THREADED
MIDRADIUS CHORD
O-RINGS
AIR XDCR
515
520
120°
CIRCULATION ABOUT Z AXIS
EACH PARTIALLY THREADED CAVITY RECEIVES "AIR XDCR", O-RINGS & HOLLOW SCREW FOR TRIPLE MIDRADIUS Γ MEAS'T OF AIR OR OTHER GASES.
30°
HOLE THRU PIPE WALL
OPTIONALLY THREADED
516
XDCR ISOLATION BLOCK WELDED OR OTHERWISE JOINED TO CLAMP "STRAP"
504b
FLUID
O-RING SEAL OR GASKET BETWEEN CLAMP AND PIPE
CLAMP "STRAP"
SECTION A-A OF CLAMP
RELIEF TO AVOID DAMPING LEAKY WAVES.
PIPE WALL
CLAMP
(FOR EXAMPLE, PIPE RISER CLAMP)
504a
512
512c
LOCATION FOR TRIPLE MIDRADIUS CLAMP-ON "RCVR"
DETAIL B
SWIRL XDCR
CLAMP
PIPE WALL
LIQUID
PIPE RISER CLAMP OR SIMILAR COLLAR OR CLAMP.
WEDGE IS PART OF CLAMP, E.G., ROD WELDED OBLIQUELY THRU STRAPLIKE BAND OF CURVED STEEL & URGED AGAINST PIPE WALL AS CLAMP IS TIGHTENED

FIGURE 13

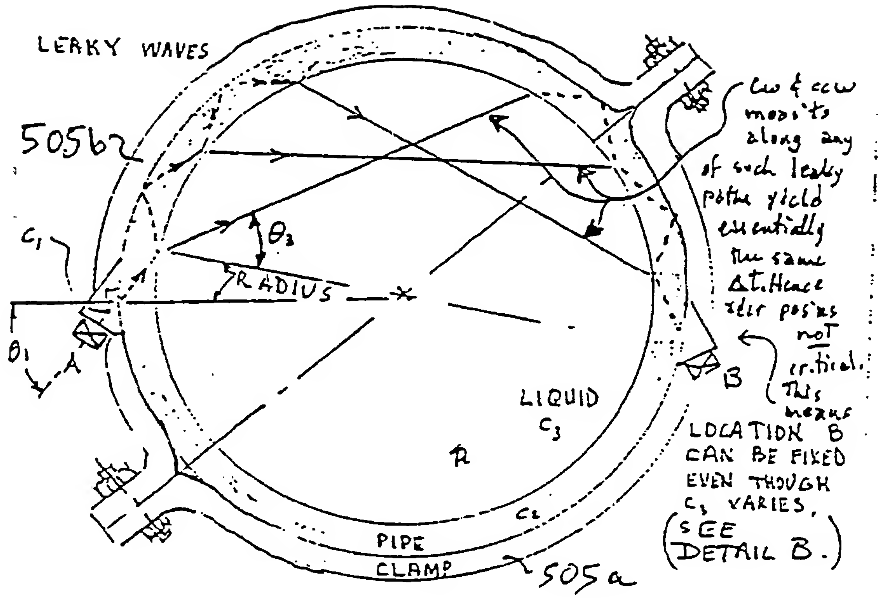

LEAKY WAVES
505b2
c_1
θ_3
RADIUS
θ_1
A
B
LIQUID
c_3
R
c_2
PIPE
CLAMP
505a
cw & ccw meas'ts along any of such leaky paths yield essentially the same Δt. Hence xdcr posi'ns not critical. This means
LOCATION B CAN BE FIXED EVEN THOUGH c_3 VARIES.
(SEE DETAIL B.)

FIGURE 13A

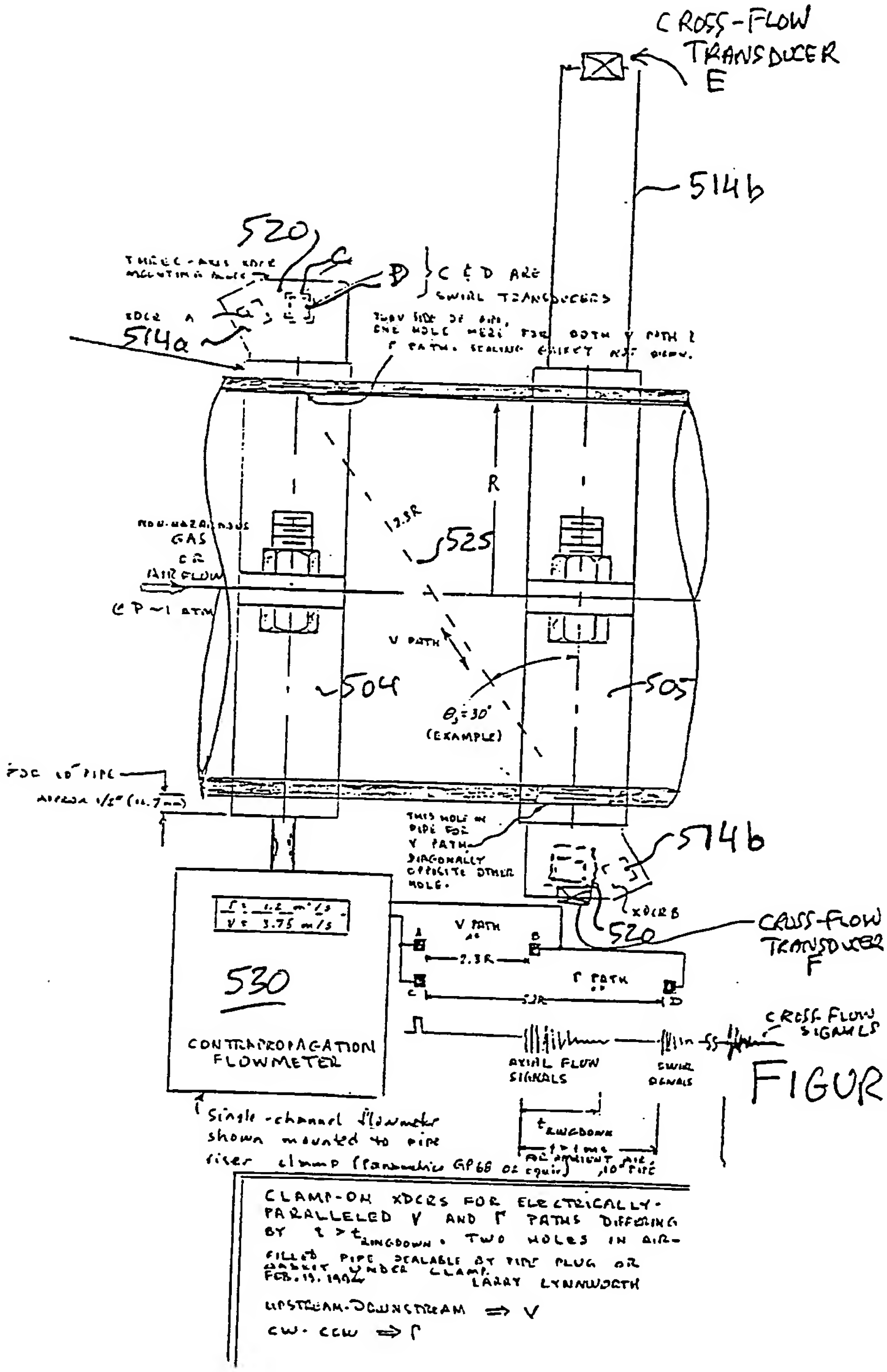

CROSS-FLOW TRANSDUCER E
514b
520
C
D
C & D ARE SWIRL TRANSDUCERS
514a
525
R
GAS
504
505
V PATH
$\theta_3=30°$ (EXAMPLE)
514b
520
CROSS-FLOW TRANSDUCER F
V PATH
Γ PATH
530
CONTRAPROPAGATION FLOWMETER
AXIAL FLOW SIGNALS
CROSS-FLOW SIGNALS
UPSTREAM-DOWNSTREAM ⇒ V
CW-CCW ⇒ Γ

FIGURE 13B

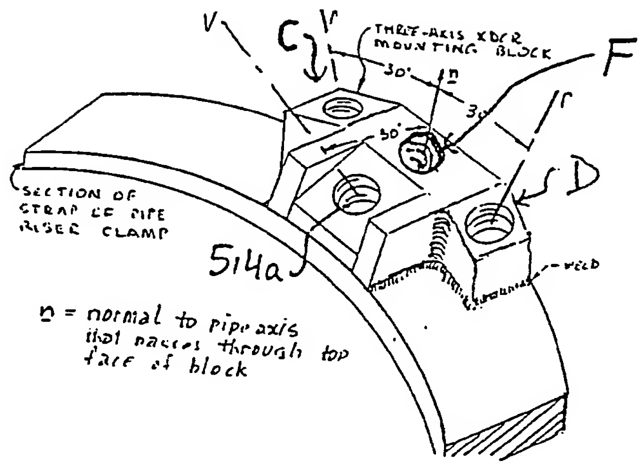

V
C
V
THREE-AXIS XDCR MOUNTING BLOCK
F
30°
n
30°
3
r
D
SECTION OF STRAP OF PIPE RISER CLAMP
514a
WELD
n = normal to pipe axis that passes through top face of block

FIGURE 13C

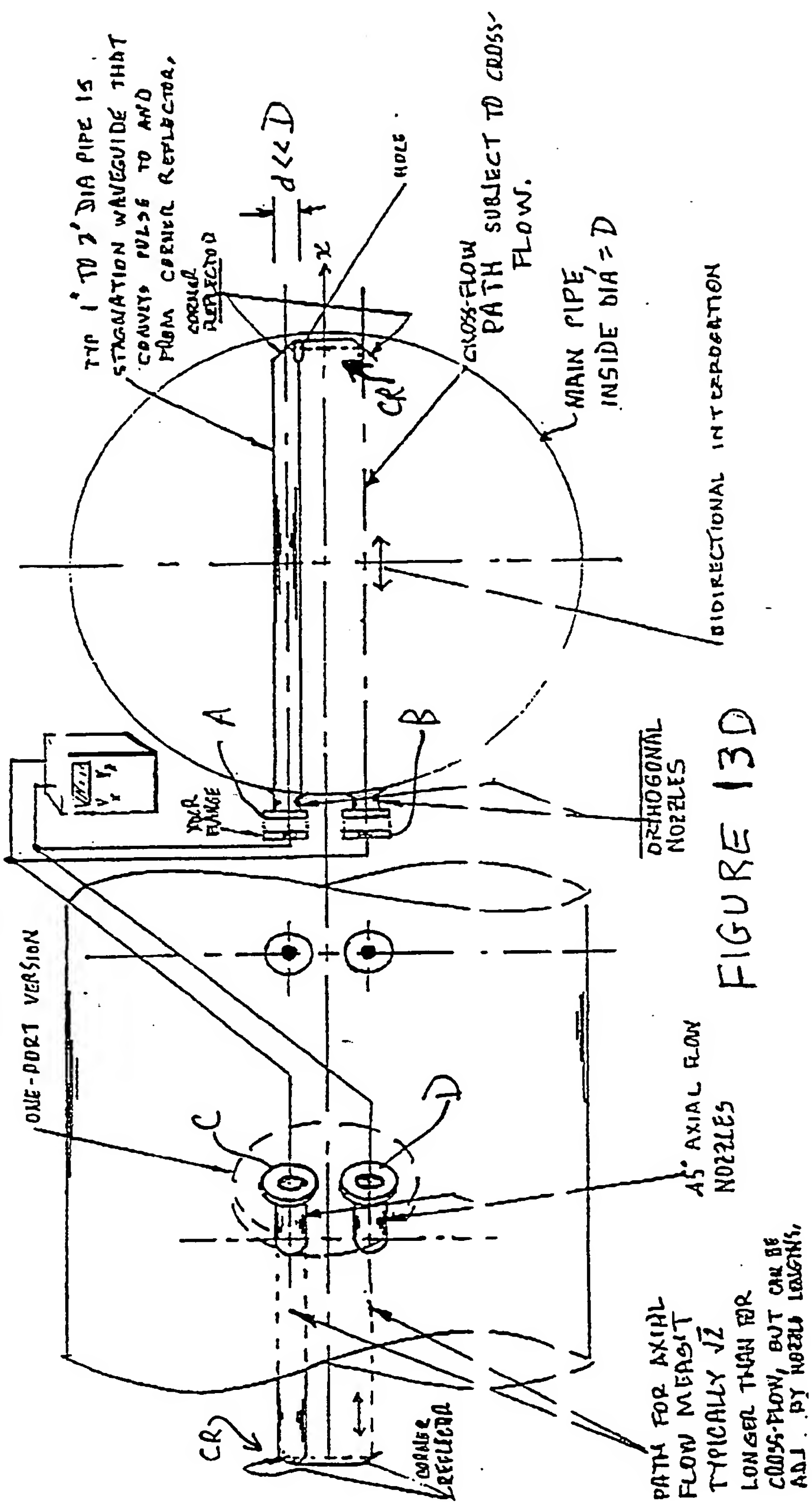
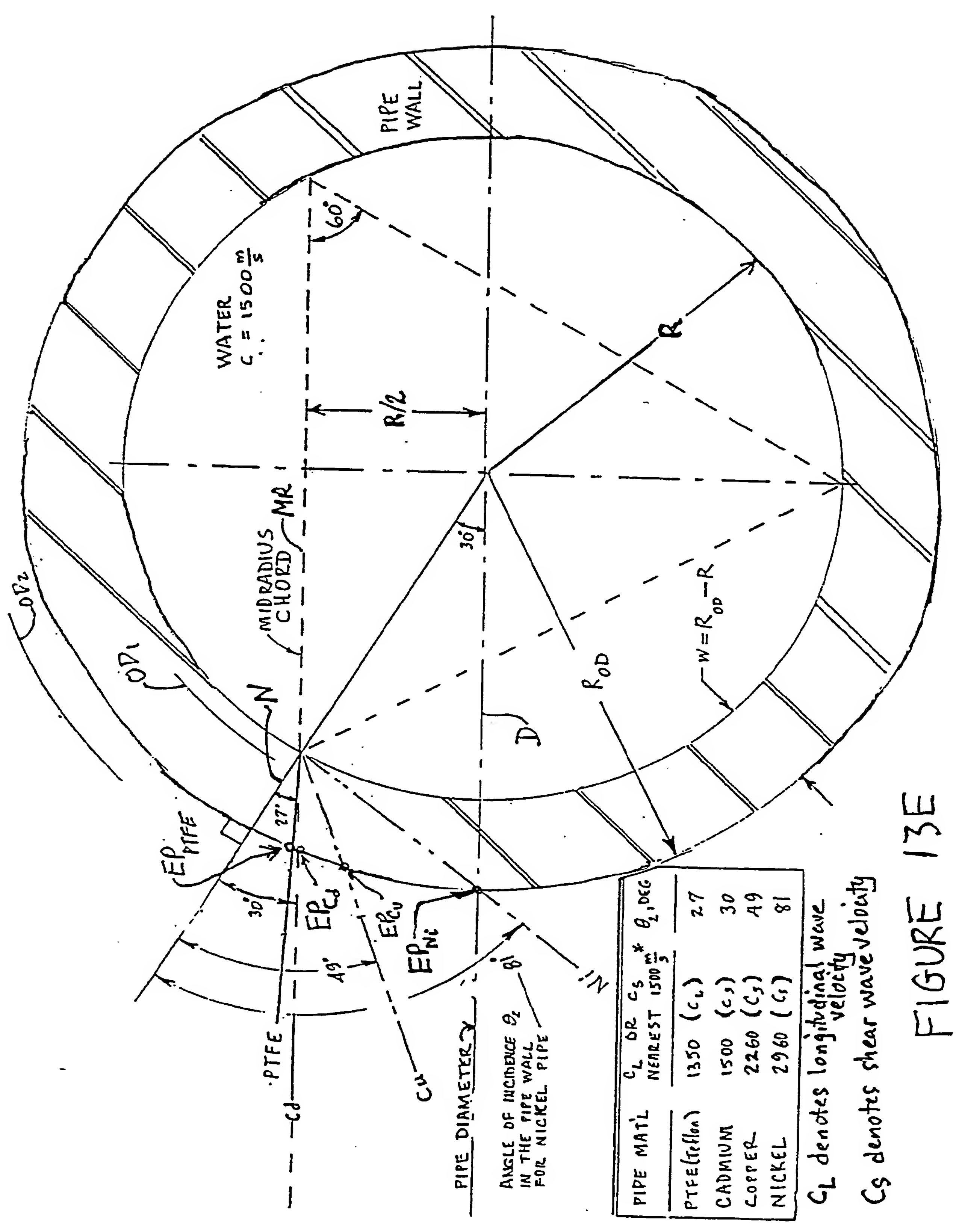

TYP 1" TO 2" DIA PIPE IS STAGNATION WAVEGUIDE THAT CONVEYS PULSE TO AND FROM CORNER REFLECTOR.
CORNER REFLECTOR
d<<D
HOLE
x
CR
CROSS-FLOW PATH SUBJECT TO CROSS-FLOW.
MAIN PIPE, INSIDE DIA = D
BIDIRECTIONAL INTERROGATION
A
B
TYP. FLANGE
ORTHOGONAL NOZZLES
ONE-PORT VERSION
C
D
45° AXIAL FLOW NOZZLES
PATH FOR AXIAL FLOW MEAS'T TYPICALLY √2 LONGER THAN FOR CROSS-FLOW, BUT CAN BE ADJ. BY NOZZLE LENGTHS.
CR
CORNER REFLECTOR

FIGURE 13D



PIPE MAT'L	C_L OR C_S NEAREST 1500 m/s *	θ_2, DEG
PTFE (teflon)	1350 (C_L)	27
CADMIUM	1500 (C_S)	30
COPPER	2260 (C_S)	49
NICKEL	2960 (C_S)	81

C_L denotes longitudinal wave velocity

C_S denotes shear wave velocity

FIGURE 13E

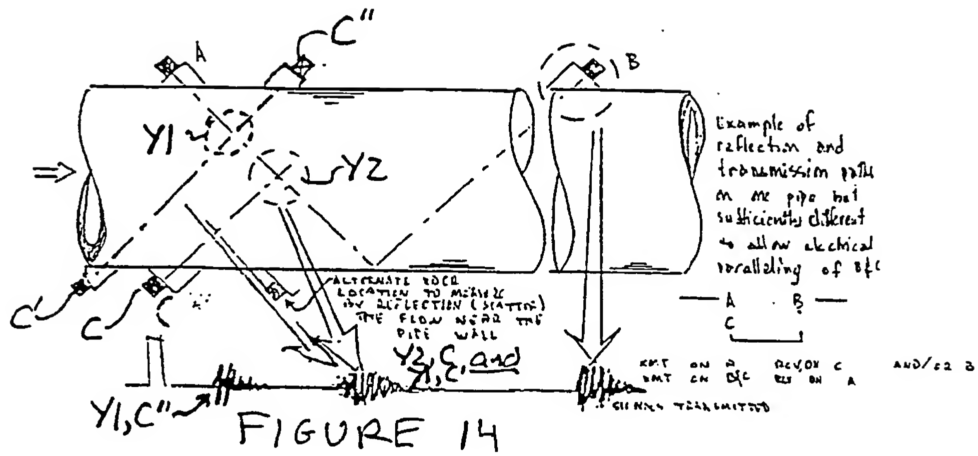


FIGURE 14

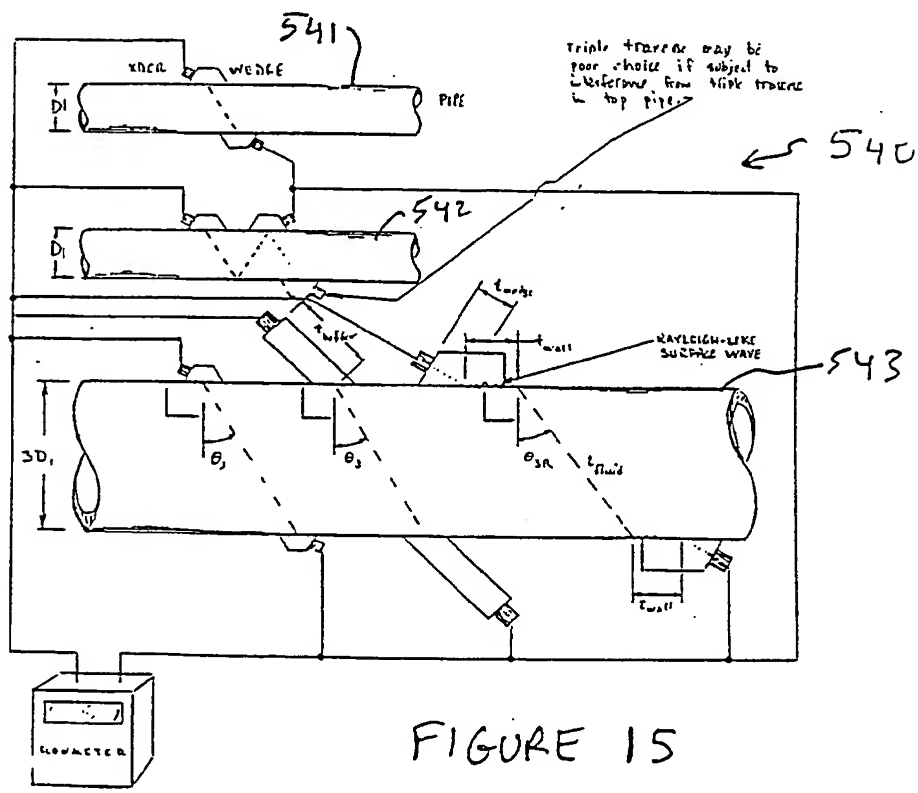


FIGURE 15

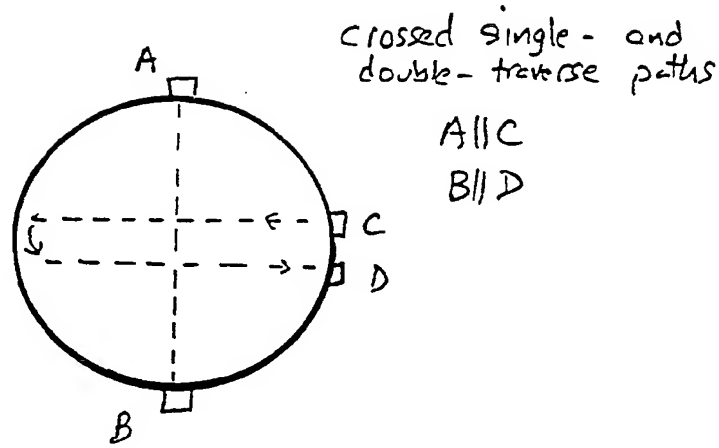


FIGURE 15A

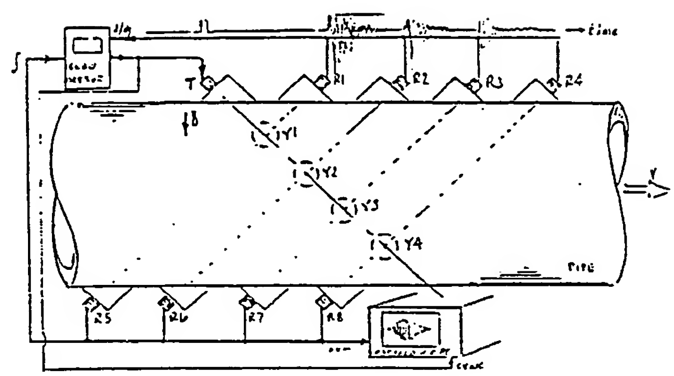


FIGURE 16

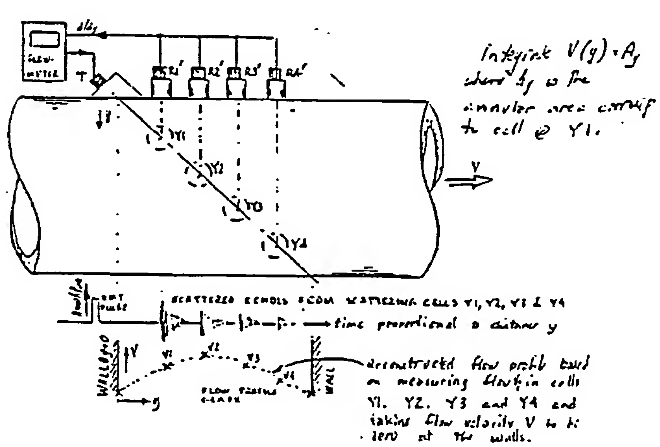


FIGURE 17

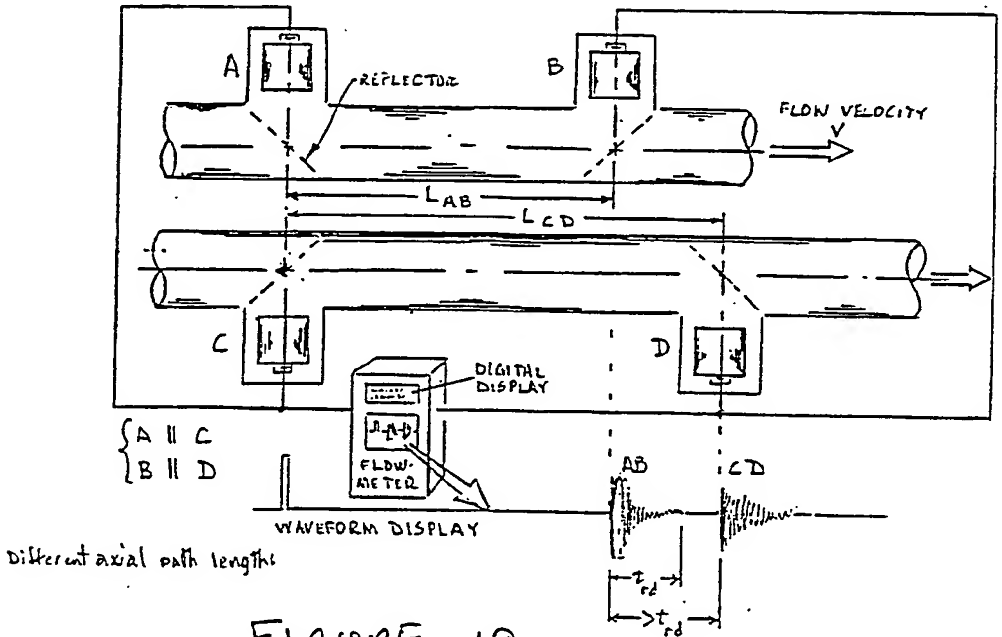


FIGURE 18

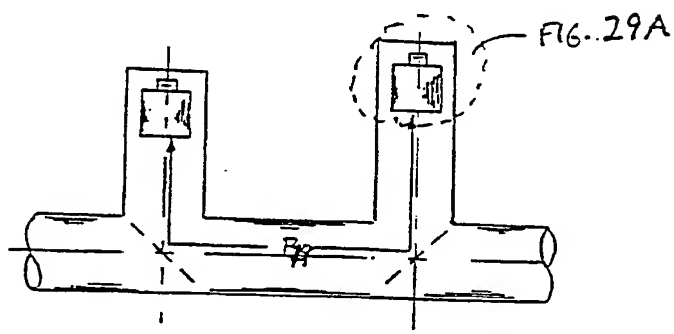


FIGURE 19

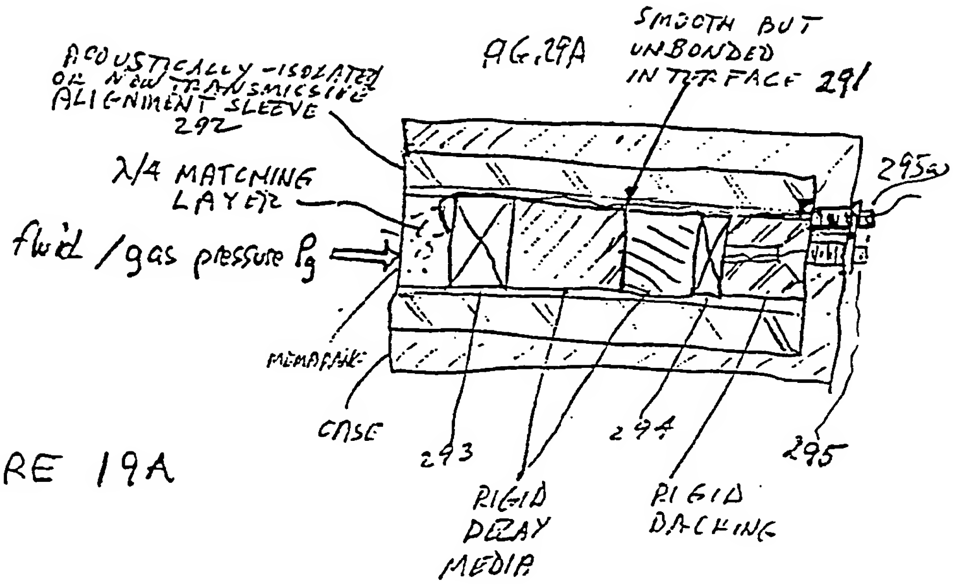


FIGURE 19A

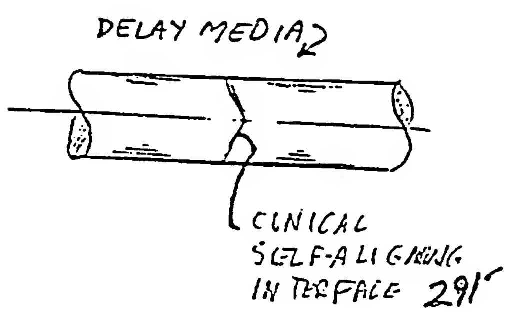


FIGURE 19B

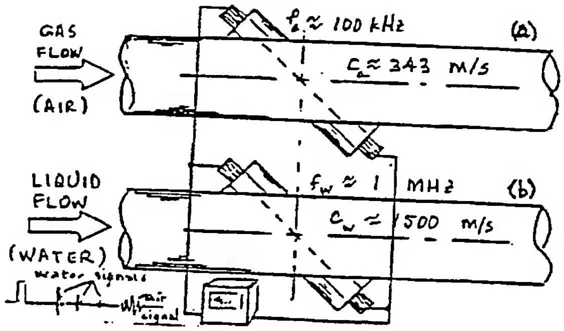


FIGURE 20

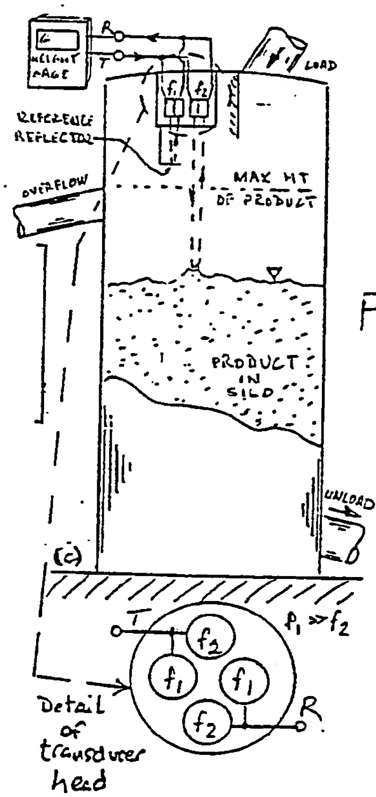


FIGURE 21

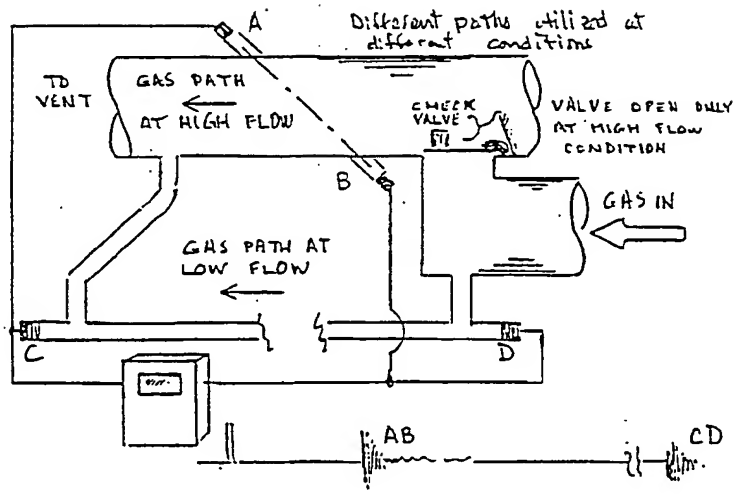


FIGURE 22

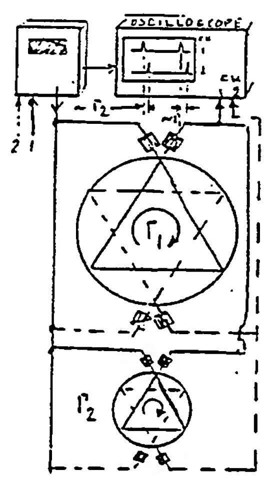


FIGURE 23

FIGURE 24A

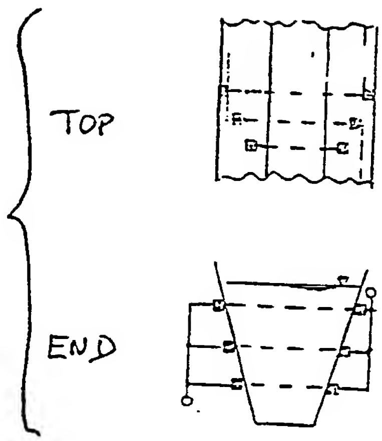


FIGURE 24B